

RILEM Bookseries

Freek P. Bos
Sandra S. Lucas
Rob J. M. Wolfs
Theo A. M. Salet *Editors*

Second RILEM International Conference on Concrete and Digital Fabrication

Digital Concrete 2020



 Springer

Second RILEM International Conference on Concrete and Digital Fabrication

RILEM BOOKSERIES

Volume 28

RILEM, The International Union of Laboratories and Experts in Construction Materials, Systems and Structures, founded in 1947, is a non-governmental scientific association whose goal is to contribute to progress in the construction sciences, techniques and industries, essentially by means of the communication it fosters between research and practice. RILEM's focus is on construction materials and their use in building and civil engineering structures, covering all phases of the building process from manufacture to use and recycling of materials. More information on RILEM and its previous publications can be found on www.RILEM.net. Indexed in SCOPUS, Google Scholar and SpringerLink.



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Rob J. M. Wolfs · Theo A. M. Salet
Editors

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Digital Concrete 2020

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ISSN 2211-0844

RILEM Bookseries

ISBN 978-3-030-49915-0

<https://doi.org/10.1007/978-3-030-49916-7>

ISSN 2211-0852 (electronic)

ISBN 978-3-030-49916-7 (eBook)

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This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

It is our great pride and pleasure to present to you the proceedings of *Digital Concrete 2020*, the 2nd RILEM International Conference on Concrete and Digital Fabrication. More than 100 papers await you, collected from around the globe.

Digital Concrete was initiated by the RILEM Technical Committee 276 Digital Fabrication with cement-based materials. Starting in 2016, this committee has stood at the cradle of an impetuously growing field of technologies and associated research. Driven by the promise of increased productivity and speed, reduced material use and cost, and enhanced geometrical freedom, digital fabrication methods with cement-based materials have taken a flight. The number of papers has tripled since the first *Digital Concrete* conference, held in September of 2018 at the ETH Zurich, Switzerland. Distinctive areas of research within the field are becoming discernable, such as mixture design, rheology & fresh state behaviour, hardened properties, and structural engineering. Technology, equipment and digital design strategies, is a particular field of research that more than ever plays a key role in the development of cement-based manufacturing. It builds new collaborations between previously unrelated fields of expertise. A significant number of contributions in each of these areas can be found in these proceedings. In addition, we also find papers aimed at applications, as well as studies on the impact of these technologies, such as life cycle and economic analyses. This mirrors the expansive growth of ‘real’ applications.

Professional associations are setting up and expanding working groups. Figuratively speaking, we are moving from childhood into adolescence. This means our capabilities are growing rapidly, and every day we can do more—better, faster, and higher. This brings joy and excitement. However, whilst our capabilities are growing, so are our responsibilities. Digital fabrication with cement-based materials will need to provide quality, safety, and sustainability. Academics and professionals need to reach out to make sure that scientific results, ranging from the quantification of ‘printability’ to shrinkage control, from low-emission binders to reinforcement, from interface properties to design methodology and many more, find their way into practice. Vice versa, lessons and needs from industry should guide research directions and priorities. *Digital Concrete* is the platform where this synergy is

forged. We extend a virtual warm welcome to you, as this 2020 edition proceeds online in tumultuous times when the COVID-19 virus shakes our world. In addition, we hope to see you in person too at the on-location *Digital Concrete 2020 (re) visited workshop* in Eindhoven in 2021.

Digital Concrete 2020 presents an outstanding line-up of keynote speakers that represent the state-of-the-art of research across the globe. Once again, *Digital Concrete* has teamed up with *Cement & Concrete Research* to deliver a dedicated special issue containing 13 papers from renowned experts in the field, including the keynote speakers. Furthermore, the Dutch magazine *Cement* publishes a theme issue in Dutch with selected proceedings papers, for the local professional market.

We would like to thank all the authors for their contributions: their excellent work provides the backbone of the conference and allows the world to learn and grow. We thank the keynote speakers and gratefully acknowledge the support of RILEM and the Scientific and Organizing Committees. A special word of gratitude goes to our sponsors, which at the time of writing included Saint Gobain Weber Beamix, Sika, and Twente Additive Manufacturing (platinum), Bekaert (gold), and BASF and Dow (Silver).

Finally, we thank you, reader and conference participant, and hope you will enjoy an inspiring conference.

July 2020

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Rob Wolfs
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Mixture Design, Admixtures and Alternative Binder



An Fe-Rich Slag-Based Mortar for 3D Printing

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Abstract. 3D printing can lead to a technological breakthrough in the construction sector. However, the sustainability aspect of 3D printing mortar can be disputable, as 3D printable mortar contains a high amount of ordinary Portland cement (OPC). The sustainability can be increased by replacing OPC with an Fe-rich slag, which originates from the metallurgical industry and is nowadays used for low-value applications. A mortar composition consisting mainly of slag and a small amount of OPC is called a hybrid mortar and is alkali-activated to ensure that the slag is participating in the binder formation. In this study, the amount of OPC is decreased significantly, down to 6 wt% and the slag content is increased up to 28 wt% over total solid content. This work investigated the effect of several components in the hybrid mixture on the early-age stiffness development, late-age shrinkage, creep and mechanical strength and is compared to a commercial OPC-based 3D printable mortar. The components, which are important to obtain a 3D printable mixture, comprise OPC, Si fume, fine limestone, superplasticizer and carbon fibres. This study shows that the additions significantly influence the stiffness and mechanical strength development of the hybrid. The shrinkage and creep behaviour of the hybrid was considerably lower compared to the benchmark material.

Keywords: Fe-rich slag · Alkali-activated materials · 3D-printing · Dynamic E-modulus · Shrinkage · Creep

1 Introduction

The construction sector is considered a low innovative sector compared to other industries [1]. Extrusion based 3D printing of construction elements can be a game-changer in the construction industry. New architectural features can be realized as 3D printing increases the freedom of movement [2, 3]. Further, 3D printing can offer several environmental and economic advantages compared to the traditional construction process. Using 3D printing can result in a decrease in construction errors, costs and a faster construction process with reduced labour cost and safety risks [4]. Currently, over 50% of the construction costs are allocated to the fabrication of formwork, which is not needed anymore when 3D printing.

The environmental aspect is, however, sometimes disputable. Ordinary Portland cement (OPC)-based 3D-printable mortars contain a significantly higher amount of OPC, from 10% up to 22% or more, compared to conventional high-performance OPC-based

mortars [5]. However, to produce 1 ton of OPC, around 0.8 ton of CO₂ is emitted, which implies that OPC is an environmentally unfriendly material [6, 7]. Research is performed on the use of precursors, alternative to OPC, for 3D printed applications in an attempt to reduce the environmental impact. Alkali-activated fly ash (FA) 3D printable mortars are mostly reported in the literature, with mechanical properties comparable to the conventional cast process [8]. Ground granulated blast furnace slag (GGBFS) can be introduced in FA-based mortars as well to increase the mechanical strength [9]. Apart from the use of alternative precursors, several raw materials suitable for cementitious as well as alkali-activated materials are used to obtain a 3D printable mixture. Silica fume can be introduced to modify the mortar consistency in such a way that the desired yield stress and viscosity of the mixture can be obtained and the extrusion and mechanical performance are improved [9, 10]. Limestone can also be used to increase the number of interparticle contacts in the mixture and to improve extrudability and buildability [11]. The amount and type of superplasticizer (SP) are important as well, as it can influence the workability and buildability of the mixture, while fibres can improve the buildability and can reduce the shrinkage behaviour [12].

Apart from the use of GGBFS, other slags, which are not yet valorised to their full potential, can be used as well as alternative precursors. In detail, slags that originate from the Cu, Pb and Zn industry differ significantly, with respect to the chemistry, from GGBFS. These slags contain a high amount of Fe and are mostly used as a filler or are landfilled. Fe-rich slag can partially replace the OPC and can participate, after alkali-activation, in the binder formation. The binder formed from an alkali-activated OPC and Fe-rich slag blend is called a hybrid binder. The use of hybrid binders can reduce CO₂ emissions up to 80% compared to OPC-based binders, although numbers vary [13, 14]. Despite the strong environmental drive, a number of properties for both the fresh and hard hybrid mortar are not yet investigated.

In the work herein, different Fe-rich hybrid mortar formulations are produced which are intended for 3D printing. The different hybrid formulations are obtained by modifying the amount of several raw materials that are important for 3D printing. These raw materials comprise OPC, SP, silica fume, fine limestone and alkali-resistant carbon fibres. The effect of these components on the early and late-age properties of the mortar are investigated and compared to a commercially available OPC-based 3D printable mortar. The investigated early-age property comprises stiffness, and late-age properties are shrinkage, creep and flexural and compressive strength. A 1 M KOH activator is used in the hybrid formulations to enable the Fe-rich slag participation in the binder, without the loss of the SP effectiveness. Using an alkali-resistant SP is important to obtain suitable rheology for printing and to reduce the amount of activator, which impact the drying shrinkage.

2 Methodology

The precursors used in the mix formulation were CEMI 52.5 R (OPC) from CRH, an Fe-rich slag, originating from the Cu and Pb metallurgical industry, and fly-ash class F (FA) from Baumineral. The ultrafine materials comprise limestone (FL) powder (BETOFILL, Euroment) and silica fume (SF) from Elkem (microsilica 920). C-fibres

(CF) were introduced in the mixture as well. Quartz sand was used as aggregate. The crystalline composition of the Fe-rich slag was analysed by X-Ray Diffraction (D2 Phaser XRD, Bruker) measuring 2theta angles from 5° to 70° at a voltage of 30 kV and a current of 10 mA. The crystal phases and amorphous content were quantified on a blend composed of the slag and 10 wt% of a standard, crystalline ZnO, after milling in a McCrone micronizing mill while using hexane (>99% pure) and corundum beads as the milling media. The XRD pattern showed that the Fe-rich slag amorphous content ranged from 70 to 85 wt%, with wüstite (3–9 wt%), spinel (10–20 wt%) and quartz (0.1–1 wt%) being identified as the crystalline phases. The chemical bulk composition of the Fe-rich slag was determined by X-ray fluorescence (XRF, spectrometer PW 2400, Philips) and is shown in Table 1. The particle size distribution (PSD) of each raw material was determined by laser diffraction in wet conditions (Beckman Coulter LS 13 320). The PSD of each raw material is given in Table 2 and shows that SF has the smallest D_{50} (0.15 μm), followed by FL (5.7 μm), OPC (5.8 μm), Fe-rich slag (8.4 μm), FA (12.9 μm) and sand (544.2 μm). The specific density of the raw materials was measured by a pycnometer according to ASTM-B417-64 and is shown in Table 2. The specific density is the largest for the Fe-rich slag (3.4 g/cm^3), followed by the OPC, FL, FA, sand and finally SF.

Table 1. The bulk chemistry of the Fe-rich slag.

Element	FeO	SiO ₂	CaO	Al ₂ O ₃	Na ₂ O	MgO	Other
Range (wt%)	35-46	20-31	11-21	2-7	0.5-2.5	0.5-2.5	2-7

Table 2. The density and the D_{10} , D_{50} and D_{90} (μm) of each raw material.

Raw material	D_{10}	D_{50}	D_{90}	Specific density (g/cm^3)
Fe-rich slag	1.6	8.4	47.1	3.4
FA	1.4	12.9	54.2	2.6
OPC	0.9	5.8	16.8	3.1
FL	1.0	5.7	16.8	2.7
SF	0.1	0.2	0.5	2.2
Sand	348.5	544.2	790.2	2.5

The precursors were alkali-activated with a 1 M KOH alkali solution. The 1 M KOH solution was produced at least 24 h prior mixing, by dissolving KOH pellets (98% pure, Sigma Aldrich) in tap water. To lower the liquid content, two additives, a MasterGlenium 65 Con superplasticizer (SP) from BASF and bassanite (99% pure, Sigma Aldrich), were used. Prior to the mortar preparation, the superplasticizer and bassanite were introduced in the alkali solution and mixed for 30 s at low speed (130 rpm). Afterwards, the precursors and ultrafine materials were gradually added for 1 min and mixed for another minute at low speed. When C-fibres were used, the fibres were introduced during the paste preparation. Finally, the sand was added for 1 min to

the mixture and the blend was mixed for another min at high speed (220 rpm). In this research, the amounts of CEMI 52.5 R (OPC), superplasticizer (SP), silica fume (SF), fine limestone (FL) and C-fibres (CF) were modified, while the amount of sand, fly ash (FA) and Fe-rich slag remained approximately constant for each formulation. The mix composition and the bulk density of the hardened samples is shown in Table 3, in which the benchmark corresponds to the commercial 3D printable mortar and M to the hybrid mix developed herein.

Table 3. The investigated mixtures with its raw materials and bulk density.

Raw material	Bulk density (kg/m ³)	OPC	Slag + FA	SF	FL	Sand	Additives	AS	CF
Benchmark	2065	/	/	/	/	/	/	/	/
M1	2160	145	742	77	77	1157	17	185	0
M2DSP	2225	145	744	77	77	1160	13	186	0
M3IFL	2264	141	724	75	141	1128	17	181	0
M4ISF	2262	140	720	140	75	1122	18	179	0
M5DOPC	2260	72	821	77	77	1158	16	185	0
M6ICF	2185	144	738	76	76	1150	19	184	9

For identifying the dynamic E-modulus in all mixtures, an ultrasonic pulse velocity test (Type IP8, UltraTest) was employed, which continuously monitored the velocity of P-waves through the sample. The fresh mortar was cast in a cylindric silicone mould, with an emitter on one side emitting a P-wave every 10 s, and a receiver on the opposite site measuring the time delay of the wave that travelled through the sample. From this time delay, the dynamic E-modulus (E-mod) was calculated, with the formula $E_{dyn}(t) = k v(t)^2 \rho$ with $k = 0.876$, which gives an indication for the stiffness. The ultrasonic measurement was initiated 8 min after mixing and lasted up to 24 h.

The fresh mixtures were cast in $4 \times 4 \times 16$ cm³ moulds and sealed for 24 h at room temperature. Afterward, the samples were demoulded and exposed to 20 °C and 65% relative humidity for 28 days. Once demoulded, two metallic pins were placed on the two long side faces of each sample and the initial distance was measured. At specific times, the length difference or displacement was measured for each sample. In this way, the effect of the mixture composition on the displacement behaviour can be identified. Two samples of each mixture were subjected to a vertical load of 15 kN after 9 days of curing to measure the total creep. 9 days of curing were necessary for the samples to develop enough strength in order to apply a load on the samples. The load was applied to the samples for 19 days and the deformation of the samples was measured at specific times. From the measured total deformation, the shrinkage is deducted and divided by the load stress (11.25 MPa) to obtain the specific creep. The 2, 7 and 28 days flexural and compressive strength of each sample were tested according to EN 196-1. Two replicates were made for each mixture to investigate the variation in displacement behaviour and mechanical strength.

3 Results and Discussion

The benchmark exhibited a steady increase in E-mod (Fig. 1) from the start of the measurement. After 2 h, the gradient in E-mod changed, from a steady to an exponential increase, which could be related to the hardening process of the material. At that moment, a rigid network structure is formed due to the hydration process. M1 measured a slow increase in E-mod, which was insignificant during the first 2 h. In mixture M1, the use of SP in excess could delay reactivity, as the SP is able to change the surface interactions of the cement particles. The early-age E-mod development is accelerated when the amount of OPC (M5DOPC) or the amount of SP (M2DSP) is decreased. In both cases, the increase in E-mod can be explained by the decreased effect of the SP. The SP is effective on the cement and ettringite surface area and when the amount of SP decreased (M2DSP), the potential for particles to agglomerate is increased [15] and less free water is available. When the amount of OPC decreased (M5DOPC) less ettringite is formed, and consequently less surface area is available for the SP to adsorb on. At a later age, from 8 h, the E-mod gradient is decreased, as less OPC was available and thus fewer hydration reactions were taking place to contribute to the binder formation. M2DSP shows at a later age an increase in the E-mod gradient compared to M1 because less SP was available to delay the reactivity. Increasing the amount of FL (M3IFL) did not influence the E-mod during the 1st h post mixing. After 1 h, however, the E-mod developed much faster compared to M1, following a similar trend as the benchmark for 2 h long. Adding FL increased the specific surface area and could act as nucleation sites. In this way, the precipitation process is accelerated and a mixture of fines in between the coarser slag particles could result in the formation of a stiffer initial network structure. The introduction of other fines, such as SF (M6ISF), accelerated the E-mod development even faster, resulting in an early-age stiffness increase comparable to the benchmark. The alkali solution could dissolve part of the SF and could form an initial silicate network which increased the stiffness and decreased the setting time [16]. The introduction of CF in the mixture (M6ICF) significantly increased the E-mod, in particular at an early-age, which was higher compared to the benchmark. Adding CF resulted in an entangled structure in the mixture, causing an increase in stiffness.

The mixtures investigated in the current research exhibited a negative displacement, which implies that the samples are shrinking (Fig. 2). The benchmark exhibited a shrinkage up to 1180 $\mu\text{m/m}$ after 28 days. This high shrinkage might be explained by the lower sand fraction in the benchmark, resulting in a less aggregate supported matrix and a higher binder content [17]. The hybrid samples demonstrated much lower shrinkage values, ranging from 491 to 800 $\mu\text{m/m}$ after 28 days. The hybrid samples evolved after 14 days to a plateau value, while the benchmark sample continued to shrink. M2DSP shows an increase in shrinkage with 30% (645 $\mu\text{m/m}$) compared to M1. The latter can be explained by the fact that SPs are generally known to reduce the shrinkage because they decrease the surface tension in the pores [18]. When a SP is used, less water is needed to cover the cement surface and more water is free. If more water is physically bonded on the cement surface and, at a later age in the binder micropores, a higher capillary tension is generated to evaporate the water. Consequently, decreasing the SP increased the

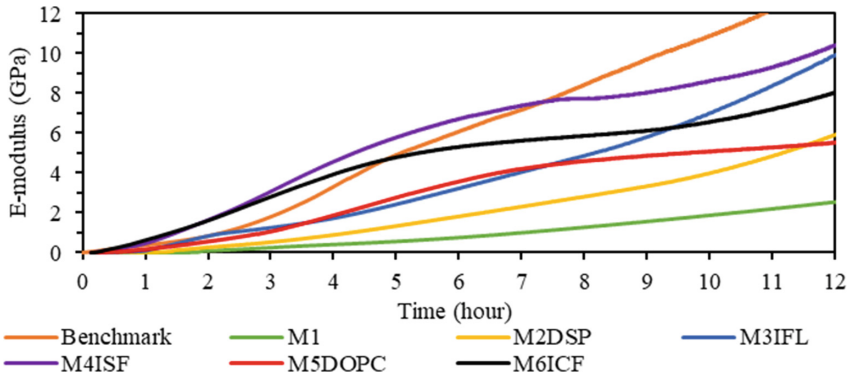


Fig. 1. The E-mod development of all mixtures from min 8 to 12 h post mixing.

shrinkage. M3IFL shows a shrinkage behaviour similar to M2DSP and is increased with 22% (594 $\mu\text{m}/\text{m}$) compared to M1. The increase in FL resulted in an increase in the surface area that needs to be covered by water. In this way, smaller pores are formed in which water is situated and consequently higher capillary tension is generated, resulting in a higher shrinkage. M4ISF measured a slight increase in shrinkage of 11% and is considered not significant. Decreasing the amount of OPC (M5DOPC) did not significantly influence the shrinkage behaviour (546 $\mu\text{m}/\text{m}$), compared to M1 (491 $\mu\text{m}/\text{m}$). The introduction of CF to the mixture (M6ICF) increased the shrinkage with 51% compared to M1, to a value of 744 $\mu\text{m}/\text{m}$. Depending on the amount and type of fibres, the fibre addition can have a negative effect on the shrinkage. The introduction of fibres can lead to an inhomogeneous mixture which can affect the shrinkage behaviour. The effect of fibre addition in hybrid binders should be investigated in the future.

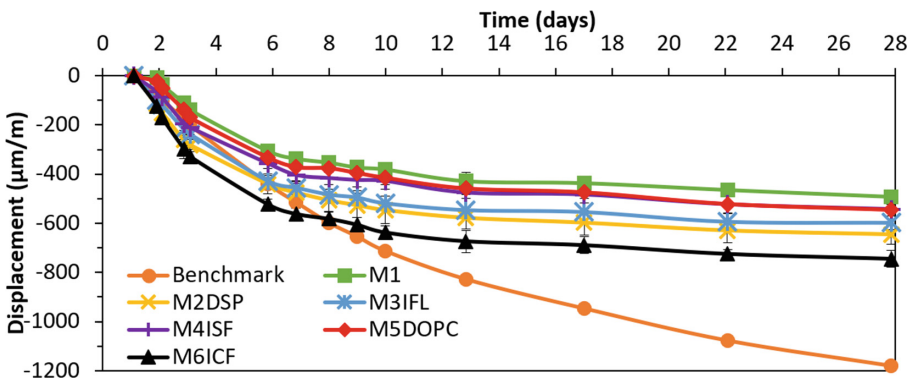


Fig. 2. The displacement of all investigated mixtures for 28 d long.

The benchmark shows the highest deformation creep, up to $-92(\mu\text{m}/\text{m})/\text{MPa}$ at 28 days (Fig. 3). The hybrid mixtures evolved towards a plateau after 28 days, while the benchmark continued to shrink. The hybrid samples show a creep which is higher for the first 2 days compared to the benchmark. The difference in creep can be explained by the higher paste to aggregate ratio in the benchmark. M1 shows the highest creep ($-60(\mu\text{m}/\text{m})/\text{MPa}$) for the hybrid samples followed by M5DOPC ($-44(\mu\text{m}/\text{m})/\text{MPa}$). In Fig. 3 it is visible that increasing the amount of FL and SF reduced the creep. M3IFL and M4ISF show a similar creep ($-34(\mu\text{m}/\text{m})/\text{MPa}$), which is decreased with 45% compared to M1. Increasing the amount of fines or surface area improved the binder resistance to deformation when subjected to a force. It is visible in Fig. 3 that the introduction of CF reduced significantly (M6ICF) the creep at an early and late age. Fibres in the sample resulted in the formation of a rigid monolith, more resistant to deformation [19]. M2DSP shows a similar creep behaviour as M6ICF, implying that a decrease in SP resulted in a stronger binder, less subjected to deformation.

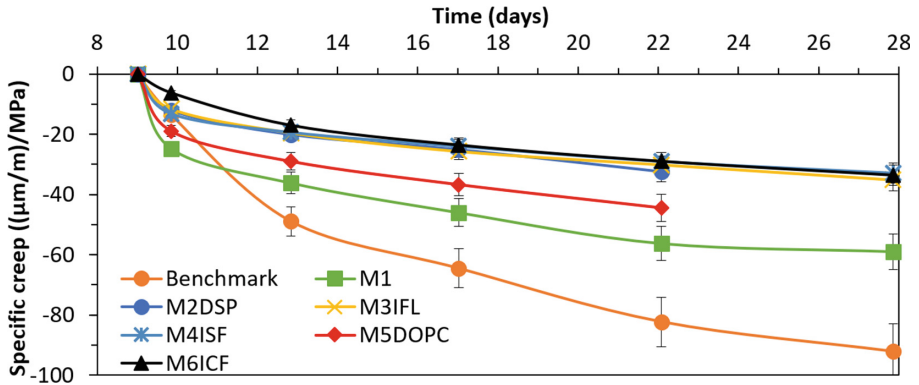


Fig. 3. The specific creep from day 9 till day 28 for all mixtures.

The 2, 7 and 28 days flexural strength of all samples are presented in Fig. 4a and show that the benchmark has a significant strength increase between 2 and 7 days (8.6 MPa). M1 shows a 28 days flexural strength of 4.9 MPa, which is almost half of the benchmark. Decreasing the SP (M2DSP) increased the flexural strength with 48%, due to the increased reactivity. Increasing the amount of FL (M3IFL) or SF (M4ISF) in the mixture increased the 2, 7 and 28 days flexural strength, with a 28 days increase of 65% and 44%, respectively. M5DOPC measured a lower flexural strength compared to M1, as less OPC is available to develop a strong binder. M6ICF obtained the highest flexural strength, and compared to M1, a 2, 7 and 28 days flexural strength increase of 51%, 71% and 83%, correspondingly. These results state that fibres increased the flexural strength properties of hybrid samples. The benchmark has the highest 2 days compressive strength (29.5 MPa) compared to all other hybrid samples (Fig. 4b). Decreasing the SP increased the 2, 7 and 28 days compressive strength properties, compared to M1, by 22%, 28% and 31%, respectively. Increasing the amount of FL (M3IFL) and SF (M4ISF) improved the 2, 7 and 28 days compressive strength by

around 40%. The addition of fines offered additional nucleation sites and improved the interparticle filling leading to reduced number of pores and improved mechanical properties [20, 21]. Decreasing the amount of OPC, resulted in a decrease in compressive strength with 25% (M5DOPC). The introduction of CF improved the 2, 7, and 28 days compressive strength with 44%, 50% and 63%, respectively.

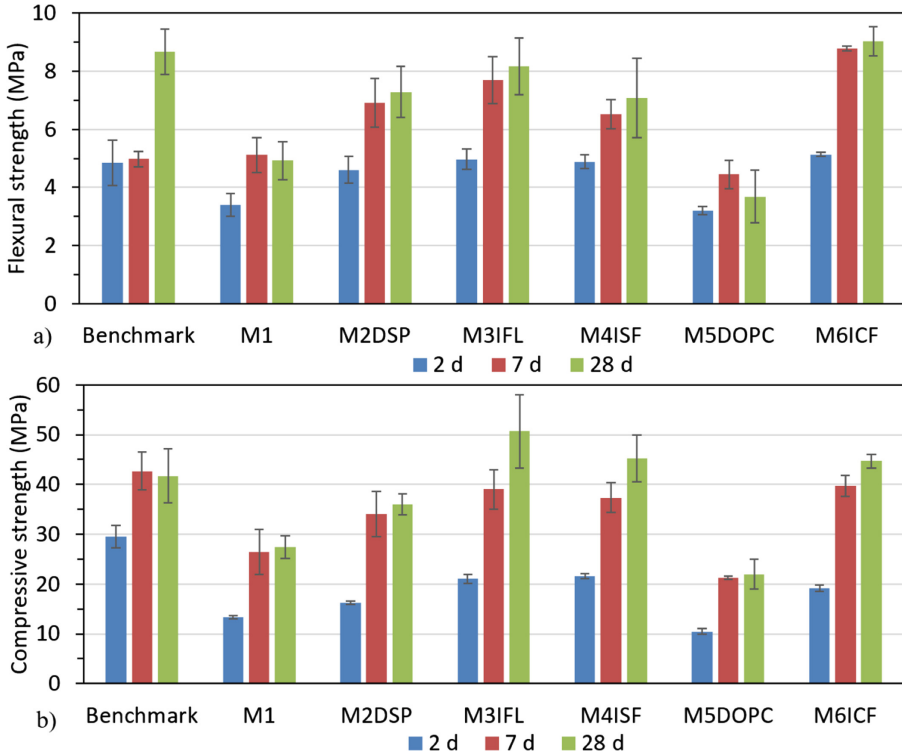


Fig. 4. (a) Shows the flexural strength, and (b) shows the compressive strength of each mixture at 2, 7 and 28 days.

4 Conclusion

In the current research, the early and late-age properties of different hybrid mortars, originating from alkali-activated Fe-rich slag were investigated and compared with a commercial 3D printable OPC-based mixture. The proportion of several raw materials in the hybrid mixture, which are important to improve the printing process, was the main experimental parameter in this study. The early-age stiffness of the commercial mixture outperformed the hybrid mixture developed herein. The shrinkage and creep of the commercial 3D printable mixture, however, was consistently higher compared to the hybrid one. The rate in dynamic E-modulus development was increased when decreasing the amount of superplasticizer. The decrease in superplasticizer had an important effect on

the late-age properties, as it increased the shrinkage with 30%, decreased the creep with 45% and increased the flexural and compressive strength with 48% and 31%, respectively. The increase in silica fume resulted in a hybrid mixture with an early-age structural build-up. Fine limestone and silica fume offered more precipitation sites to develop a stronger binder which resulted in an increase in flexural and compressive strength of around 40% and a decrease in creep of 45% for both. The amount of OPC in the hybrid mixtures can influence the effectiveness of the superplasticizer and mechanical properties. Decreasing the amount of OPC resulted in a decreased plasticizing effect and consequently an earlier dynamic E-modulus development. However, when less cement was available, a weaker binder was formed which negatively affected the mechanical properties. The addition of carbon fibres resulted in the development of a high early-age dynamic E-modulus. Carbon fibres significantly increased the flexural and compressive strength, by 83% and 63%, respectively, and decreased the creep by 45%. Carbon fibres seemed to increase the shrinkage, a behaviour that should be further investigated. This study demonstrated that hybrid binders, originating mainly from Fe-rich slags, reached suitable late-age properties, although the early-age properties still can be improved.

Acknowledgements. The authors would like to thank B. Rijssen and M. Suijs for their support in performing the measurements. This research has received financial support of the Center for Research, Recovery, and Recycling (<https://wp.wpi.edu/cr3/>).

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Enhancing Buildability of 3D Printable Concrete by Spraying of Accelerating Admixture on Surface

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Abstract. The buildability of printable concrete signifies the ability of the printed structure to retain the extruded shape and to sustain the dead load of subsequent layers on first extruded layer without collapse. Higher buildability can help in construction of tall sections in minimum possible time. The buildability depends on structural build-up rate which is controlled by cement hydration (chemical) and interaction between particles developed by flocculation (physical). In several ongoing research studies related to 3D printing, a common method for dispensing the accelerator in concrete is by adding it at the nozzle. This study aims at developing a method to increase the buildability by spraying the accelerator at higher dosages (>8% by weight of cementitious material) post printing. In the print of a full-scale specimen, an empirical method of first printing up to n layers, followed by spraying the accelerator up to $n-2$ layers (where $n > 2$) from base was done. Based on the success of this empirical study, a controlled laboratory assessment was performed. The study is divided into three parts - a) the enhancement in buildability is assessed by printing a structure of 200 mm height with spraying of accelerator, b) the depth of penetration is determined by microstructure study using XRD, c) the build-up and flow value is determined for different dosages of accelerators. The study provides a way of application of accelerating admixture in digital printing to attain higher buildability in lesser time.

Keywords: Buildability · 3D printing · Accelerator · Structural build-up

1 Introduction

Buildability of 3D printable concrete is the ability of the printed layers to sustain the dead loads due to self-weight of that layer and weight of subsequent layers. Buildability is considered in terms of both geometrical and material properties. The simplest measure of buildability is taken as deformation of lower layers [1, 2]. It is also mentioned as the number of layers to be printed without collapse while retaining the extruded shape and with minimum deformation in lower layers [3].

One of the major factors affecting buildability is the yield strength of the printable concrete. The increase in yield strength increases the buildability [4, 5]. Buildability is affected by the recovery of original viscosity and yield stress by a layer before the deposition of next layer [6]. The yield strength increases with the elapsed time [7] and

thus the buildability is affected by the printing time gaps. Another critical criterion for buildability is bond strength, which depends on the open time (change in workability with time) [3, 4].

The buildability of a 3D printable concrete is seen to be affected by rheological parameters, mechanical strength parameters, dimensions of structures and printing process [5, 8–10]. Further, different models are developed for buildability such as an analytical constitutive model to predict the maximum number of printed layers (without collapse) based on only rheological parameters [11], and numerical model for early age mechanical characterisation [12].

The buildability is enhanced by application of different types of admixtures (chemical and mineral) into the mix. Researchers used nanoclay [1, 10], calcium sulfoaluminate [4] and other mineral admixtures to enhance the buildability. The effect of chemical admixtures like accelerating admixture on the workability is studied and it is reported that the shear strength increased quadratically with the increase in dosage of accelerator [3]. The accelerator can be either added in mixer or at print head [13, 14]. The addition of supplementary cement materials at the mixer enhances the static yield strength (due to flocculation), whereas the addition of accelerating admixture can lead to early setting and affect the printing process in case of interruptions due to machine failure, etc. [13]. A combination of retarders, accelerators and thickening agent can also be used [15].

The addition of alkali-free setting accelerator at the printhead is suggested by Nerella et al. [13]; for a dosage of 2.5% of accelerator by weight of binder, the Bingham yield strength was six times higher than reference paste. The alkali-free accelerator primarily contains aluminium sulphate [16], which accelerates the crystallisation of ettringite [17]. It can be concluded that the application of accelerators will affect the microstructure which further affects the rheology as discussed by many researchers [18–21]. Hence, the addition of accelerator will have a direct effect on the rheological behaviour as well as the setting/hardening of the mix, which will affect the buildability.

2 Significance of Research

The objective of the paper is to understand the effect of alkali-free aluminium sulfate accelerator on the hydration phenomenon, strength development and flow properties of the 3D printable mix, and to develop a new method for application of accelerating admixture to enhance buildability of 3D printable concrete.

3 Materials and Methods

Portland cement and processed fly-ash are used with the chemical compositions shown in Table 1.

Table 1. Chemical composition of Portland cement and fly ash

Chemical composition	Quantity (% by mass)	
	Portland cement	Fly ash
Cao	64.59	1.28
SiO ₂	19.01	59.32
Al ₂ O ₃	4.17	29.95
Fe ₂ O ₃	3.89	4.32
(Na ₂ O) _e (alkalinity)	0.16	0.16
MgO	0.88	0.61
LOI	1.40	

The particle size (grain diameter) as per sieve analysis/laser diffraction for quartz sand ranges from 10 to 2000 μm , for Portland cement from 0.1 to 60 μm , and for fly-ash from 0.1 to 12 μm . The alkali-free accelerating admixture is used in different dosages for the tests and is mentioned in the methodologies. The mix design and properties of the constituent materials are shown in Table 2.

Table 2. Mix design and properties of the constituent materials

Material	Quantity kg/m^3	Properties
Ordinary Portland cement (OPC)	660	Conforming to IS 12269
		Specific gravity of 3.15
		Initial setting time of 195 min
Class-F fly ash (processed)	165	Conforming to ASTM C618
		Specific gravity of 2.6
Quartz Sand	1211	Specific gravity of 2.68
		Water absorption of 2.05%
Water	289	Water/cement = 0.32
PCE based superplasticizer	0.05% (solids) of weight of binder	Liquid form with solid content of 34%
Methyl cellulose-based Viscosity Modifying Admixture (VMA)	0.22% of weight of binder	Level of viscosity: 60000 $\text{mPa}\cdot\text{s}$ (according to Hoppler)
Polypropylene fibers	1.8	40-micron thickness and 12 mm length

3.1 Assessment of Accelerator Spraying on Buildability of a Printed Structure

The mixing is done in a pan type mixer. The dry mix of cement, quartz sand and fly ash is mixed with water and superplasticizer for 10 min, VMA is then mixed for 5 min followed by fibers for around 5 min to get a homogenous mix. Two rectangular

sections of 300 mm * 300 mm are printed. In the second section, accelerating admixture (quantity equivalent to 8% by weight of binder) is sprayed on the outer surface. The buildability is quantified in terms of height of 20 printed layers and the vertical deformation (compression) of bottom layer.

3.2 Assessment of Effect of Accelerator Spraying in Large Scale Printed Structures

Two large-scale modules are printed. In the first printed module, panels of 8–15 layers of 15 mm thickness are printed, and then assembled together with the help of a binding mortar, in order to complete the ~2.1 m tall structure. In the second module, 20 mm thick layers are printed continuously, but alkali-free accelerator is sprayed on the surface at specific points, to bring up to a final height of ~1.5 m. The deformation of lower layers is measured for buildability.

3.3 Tests Performed in Lab to Assess the Accelerating Admixture

The mixing is done in a Hobart planetary type mixer. The sequence of batching and mixing is the same as in the case of the concrete in pan mixer. Fibers are not added in the cube compressive strength tests, flow value tests, and accelerating admixture spray tests.

In first set of experiments, the effect of accelerator addition on hydration, setting time, compressive strength and flow value is tested. Semi-adiabatic calorimetry test (EN196-9) is performed to deduce the effect of different dosages of accelerators on the hydration rate. The initial setting time of cement with 0%, 1%, 2%, 4% and 8% accelerator are determined as per IS:4031(Part 5)-1988. The penetration test for determination of setting time on the 3D printable mixture is done as per ASTM C403 and IS:8142-1976 on four mixes with 0, 1%, 2% and 3% accelerator, added at the last step of the mixing process. For compressive strength determination as per IS 4031 (part 6)-1988 (0 and 3% accelerator), only two mixes are used. A flow table test is performed as per ASTM 1437-15 with 0 to 3% accelerator dosages.

The next set of experiments are performed to understand the penetration depth of the sprayed accelerators and its effect on compressive strength by spraying the accelerator (after one hour of casting imitating the time for mix to reach from mixer to nozzle head at worst condition) on either one vertical surface or both vertical surfaces at a dosage of 16% by weight of binder (one side) and 12% by weight of binder (6% on each surface) as shown in Fig. 1. The XRD analysis is performed on the specimens taken from surface and interior at intervals of 3 h after spraying (16% bwob) and the depth of penetration is assessed. The specimens are kept immersed in isopropanol for 3 days and further in vacuum drying for at least 3 days.

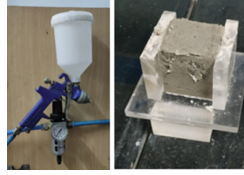


Fig. 1. Accelerator spray gun and cubes on which accelerator is sprayed

4 Results and Discussions

The buildability of the printed structures is evaluated based on total height and lower layer compression. The first 10 layers are printed, and after a gap of 10 min next 10 layers are printed at a print speed of 25 mm/s. The printed structures are shown in Fig. 2. The accelerator is sprayed after printing of every two layers. The accelerator is sprayed after printing of every two layers on the outer vertical side, the sprayed accelerator can move to layers beneath. The spraying cycle is synchronised with the printing. The result of the buildability test is presented in Table 3.



Fig. 2. Buildability test for printed structure a) without accelerator, b) accelerator sprayed, and c) Plan view of the structure

Table 3. Buildability test data for sprayed and unsprayed specimens

Property	Quantity (mm)
Target height for both structures	200
Target height of individual layers	10
Total height of first structure (without accelerator)	182
Bottom layer height after printing of 10 layers for first structure	7
Bottom layer height after printing of 20 layers for first structure	4
Total height of second structure (with accelerator)	197
Bottom layer height after printing of 10 layers for second structure	9
Bottom layer height after printing of 20 layers for second structure	9

The results in Table 3 clearly indicate that spraying of accelerator is enhancing the buildability. The net height reduction for sprayed sample is 1.5% against 9% of the other structure. The bottom layer of the sample with accelerator sprayed on the surface is not getting compressed by the weight of subsequent ten layers whereas for the other structure, the bottom layer is getting compressed from 7 mm to 4 mm. It can be said that the lower layers are becoming stiff under the action of accelerating admixture, leading to better buildability. It can be said that the lower layers are becoming stiff under the action of accelerating admixture, leading to better buildability. The desired amount of accelerator on each layer is not assessed in this study and is the limitation of the study. Further studies are performed to understand the reason of this behaviour.

Two large scale structures are printed. One of the structures is printed with accelerator sprayed on the surface (at certain points on demand unlike the structure in Fig. 2b) as shown in Fig. 3. The structure in Fig. 3a was printed in panels and the target height of lower layer was 15 mm, but the achieved height was 9 mm. The layer is compressed by 40%. For the structure in Fig. 3b, the printing was done continuously with simultaneous spraying of accelerator on the vertical surfaces of layers showing higher deformation. The target layer height is 20 mm and the achieved height is 15 mm, hence, the layer is compressed by 25%. It can be concluded from this observation that the spraying of accelerator on the surface can enhance the buildability.

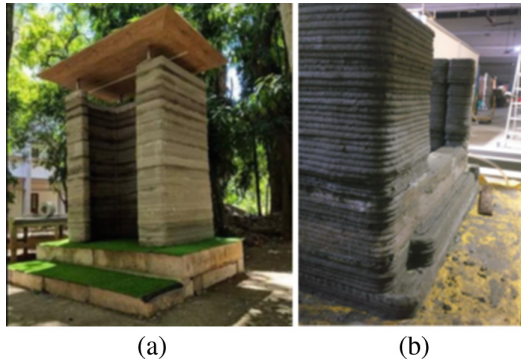


Fig. 3. Large scale printed structures a) without accelerator, b) with accelerator spraying

The alkali-free accelerator is assessed further to understand the above behaviour. The results of the semi-adiabatic calorimetry evaluation, shown in Fig. 4, indicate the effect of different dosages of accelerator in the hydration process of the mix. It can be seen from the Fig. 4, that the material with higher accelerator dosage attains the peak earlier (increase in build-up rate) reducing the dormant time.

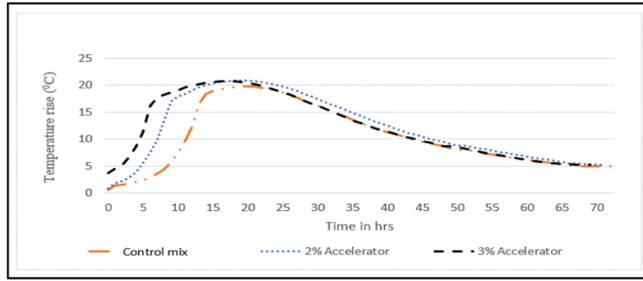


Fig. 4. Semi-adiabatic calorimetry study for different dosages of accelerators

The results of the initial setting time of cement paste with different dosages of accelerating admixture are presented in Fig. 5.

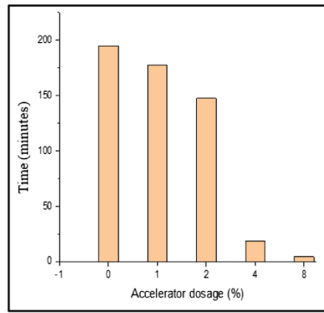


Fig. 5. Initial setting time of cement paste with different dosages of accelerator

The setting is rapid on addition of higher dosages of accelerators. The application of 8% of accelerator by weight of cement reduced the setting time to 4.5 min, where 2% accelerator dosage reduced the setting time from 3 h 15 min to 2 h 30 min. So further study with penetration resistance test is decided for accelerator dosages of 1%, 2% and 3% as shown in Fig. 6. The initial setting time is corresponding to 3.43 N/mm² and final setting time to 26.97 N/mm². The 3% accelerator dosage reduces the initial setting (3.5 h) and final setting time (6.2 h) of the mortar in a considerable amount with respect to control mix. For the mix with 1% and 2% accelerator, the initial and final setting time for the mortar are close but around 1.5 and 1 h less than control mix respectively. The build-up starts after 2 h for the mix with 3% accelerator. That means if the dosage is higher the build-up can start early. The formation of ettringite accelerates (as discussed in the Sect. 1) rapidly under higher dosage of accelerating admixture as observed from Figs. 5 and 6.

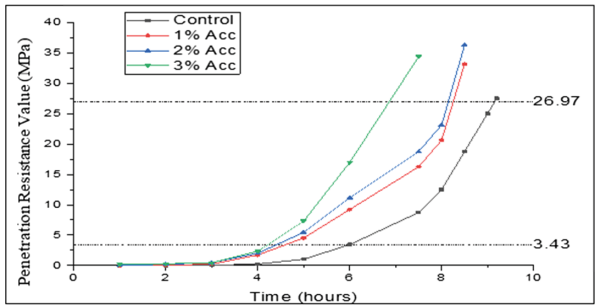


Fig. 6. Penetration resistance curve for different dosages of accelerator

The flow table test is performed on the accelerated mix as shown in Fig. 7. The flow value reduces drastically on the addition of accelerator. The yield strength is increasing, and hence higher number of blows are required for the same flow. The spraying of accelerator also leads to increase in the stiffness of outer layer by increasing the yield strength as well as leading to early build-up.

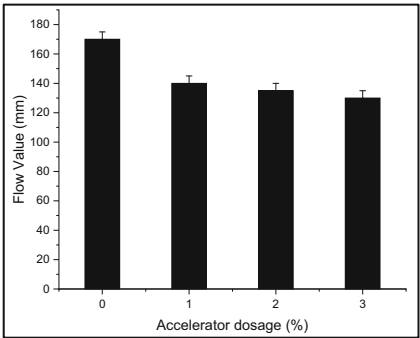


Fig. 7. Flow value with different dosages of accelerator

Further, the accelerating admixture is sprayed at a pressure of 1 bar from 50 mm from surface. The depth of penetration is assessed by X-Ray Diffraction test. The formation of ettringite is seen up to the depth of 5–7 mm from the surface, whereas the layer beyond is not found to be having ettringite as shown in Fig. 8. So, the depth of penetration is up to 5–7 mm from surface. The compressive strength for 1 day is reported in Table 4. There is no significant strength gain for sprayed accelerator whereas for mixed accelerator the strength increases to twice the value of the control mix.

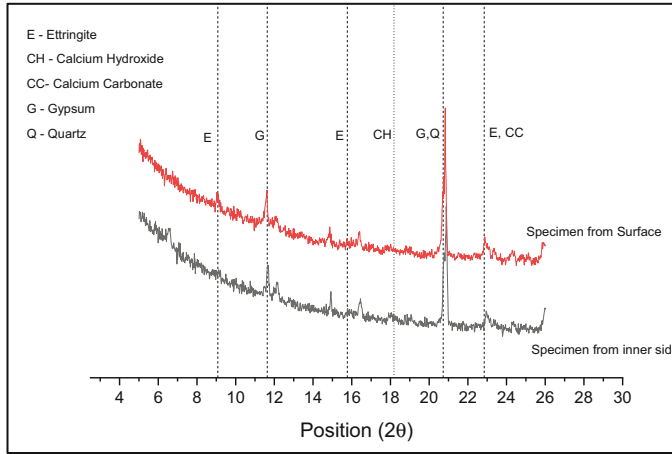


Fig. 8. XRD data for determining depth of penetration of accelerator

Table 4. 1-Day compressive strength

1-Day compressive strength	Strength (MPa)	Standard deviation in %
Control mix	5.80	10
Mix with 3% accelerator (admixed)	11.40	5
16% accelerator sprayed on one side	5.85	8
6% accelerator sprayed on each side	5.95	10

5 Conclusion

The spraying of accelerator on the surface of printed structure enhances the buildability. The application of the accelerating admixture is done post-printing and it can be applied on an on-demand basis. The alkali-free accelerating admixture penetrates up to 5–7 mm under a 1 bar pressure as seen from the formation of ettringite on the outer layers after 3 h from spraying. The accelerator increases the rate of flocculation as well as hydration and enhances the yield strength of the outer layer. This outer layer acts as a sacrificial layer and arrests the plastic deformation of the layers under subsequent loads. The structural build-up is seen to be accelerated by the application of the admixture as observed in semi-adiabatic calorimetry, penetration resistance and flow table tests.

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Effect of Wollastonite Micro-Fiber Addition on Properties of 3D-Printable ‘Just-Add-Water’ Geopolymers

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Abstract. This paper reports the effects of addition of wollastonite micro-fiber on the properties of a 3D-printable geopolymer for digital construction applications. Having a ‘one-part’ (just-add-water) mixture formulation, the developed 3D-printable geopolymer uses a small amount of activator powder, instead of using a large amount of the commonly used activator solution. A small portion of fine sand (10% by weight) was substituted by wollastonite powder. The fresh properties (including shape-retention-ability and yield stress evolution), as well as the hardened properties (including compressive strength and flexural strength) of the mixtures were measured. The results showed that the addition of wollastonite significantly increased the shape-retention-ability and static yield stress of the fresh mixture, which is beneficial in terms of buildability of the material. Furthermore, the results showed that addition of the wollastonite considerably enhanced the flexural strength, while the compressive strength of the hardened specimens remained unchanged.

Keywords: 3D concrete printing · One-part geopolymer · Solid activator · Wollastonite · Mechanical properties · Yield stress evolution · Shape-retention-ability

1 Introduction

As a novel construction technique, three-dimensional concrete printing (3DCP) allows fabrication of concrete components with complex geometries by using additive manufacturing techniques. 3DCP has received a considerable amount of attention from the academia and industry in recent years due to its potential advantages when compared with the conventional construction approach (i.e. casting concrete into a formwork) [1, 2].

One of the current major challenges that limit the growth of 3DCP is the limited range of concretes that are suitable for the extrusion-based printing process [2]. To overcome this challenge, the authors of this study have recently formulated ambient temperature-cured ‘one-part’ geopolymers suitable for extrusion-based 3DCP process [3, 4]. The developed printing material has a ‘one-part’ mixture formulation, which

considerably improves its commercial feasibility and large-scale application in the construction industry.

Another major challenge of 3DCP is inclusion of steel reinforcement into the extrusion process. Considering the nature of the 3D printing process, micro-fiber can be directly added into the fresh printable concrete mixture to enhance the flexural and/or tensile strengths of the printed components, which in turn, decreases the need for using conventional steel bars.

In this study, wollastonite (i.e. a naturally formed calcium silicate crystal) micro-fiber was used as partial replacement of fine sand to enhance the mechanical properties of the recently developed 3D-printable ‘one-part’ geopolymer [3]. The effect of wollastonite addition on shape-retention-ability and yield stress evolution of the fresh mixture was investigated. In addition, the compressive strength and flexural strength of the printed specimens were tested in different loading directions. The results were compared with those of the control mixture without wollastonite.

2 Experimental Procedures

2.1 Materials and Mixture Proportion

The geopolymer precursors used in this study were a combination of a ground granulated blast furnace slag (denoted as “slag”) and a low calcium (Class F) fly ash. The slag was supplied by Independent Cement and Lime Pty Ltd., Australia, while the fly ash was supplied by Cement Australia Pty Ltd. The solid activator was a combination of anhydrous sodium metasilicate powder with a modulus ratio (M_s) equal to 0.9 (where $M_s = n\text{SiO}_2/n\text{Na}_2\text{O}$, $\text{SiO}_2 = 46 \text{ wt\%}$ and $\text{Na}_2\text{O} = 51 \text{ wt\%}$) and GD Grade sodium silicate powder with a modulus ratio (M_s) equal to 2.0 ($\text{SiO}_2 = 54 \text{ wt\%}$ and $\text{Na}_2\text{O} = 27 \text{ wt\%}$). The anhydrous sodium metasilicate powder was supplied by Redox Pty Ltd., Australia, while the GD Grade sodium silicate powder was supplied by PQ Australia Pty Ltd., Australia.

Three different sizes of silica sands were used in this study. The relatively coarser sand denoted as “C-sand” had a D50 of 840 μm , while the relatively finer sand denoted as “F-sand” had a D50 of 176 μm . The sand with relatively medium size particles denoted as “M-sand” had a D50 of 498 μm . The F-sand was supplied by TGS Industrial Sand Ltd., while both M- and C-sands were supplied by Sibelco Australia Ltd. Wollastonite powder with an average aspect ratio of 19:1 was supplied by Jilin Shanwei Wollastonite Mining Co., Ltd., China. Further details of the wollastonite can be found in the authors’ previous study [5]. Sucrose powder supplied by Chem-Supply Pty Ltd., Australia was used as a retarder.

Table 1 shows the mixture proportions of the printable geopolymer. The mixture proportion of M1 was adopted from the authors’ previous study [3]. In both mixtures, the mass ratio of slag to fly ash was constant and equal to 1.0. The mass ratio of anhydrous sodium metasilicate powder to GD Grade sodium silicate powder was also constant and equal to 1.0. In mixture M2, 10% of F-sand was substituted by wollastonite powder, and the water content of the mix was adjusted in such a way that both M1 and M2 exhibited comparable workability.

Table 1. Mixture proportions of 3D printable one-part geopolymers.

Mix	Geopolymer precursors	Act.	F-sand	M-sand	C-sand	Wollastonite	Water	Retarder
M1	1.0	0.1	0.660	0.320	0.520	–	0.360	0.005
M2	1.0	0.1	0.594	0.320	0.520	0.066	0.377	0.005

Note: All numbers are mass ratios of the geopolymer precursors (fly ash + slag) weight.

Act. denotes solid activators.

2.2 Mixing, Printing and Curing

All solid materials including slag, fly ash, solid activators, silica sands, retarder and wollastonite (if any) were dry mixed in a 20 L Hobart mixer for about 3 min. Then, tap water was slowly added to the materials and the mixing process was continued for further 10 min to obtain a consistent mixture.

A gantry-type 3D printer with an effective printing volume of 1.8 m × 1.6 m × 1.8 m (L × W × H) equipped with an auger-type extruder with a circular nozzle with a diameter of 20 mm was used in this study. For each mixture, two solid slabs with dimensions of 300 mm × 300 mm × 30 mm (L × W × H) were 3D printed. The slabs were made of three layers, where the height of each layer was 10 mm. The printing speed and extrusion rate adopted for printing of the slabs were 30 mm/s and 0.6 L/min, respectively.

After printing, the printed slabs were covered with a plastic sheet and left on the printing platform for 24 h. Although the developed 3D-printable geopolymer mixture can be cured at ambient temperature, heat curing was adopted in this study to accelerate the geopolymerisation reaction and rate of strength gain. It should be noted that at the end of the heat curing process the strength of heat-cured geopolymer typically reaches more than 90% of its 28-day ambient temperature cured strength [6, 7]. The printed slabs were transferred to a sealed container to avoid moisture loss during the heat curing process. All printed slabs were then cured inside an oven at a temperature of 60 °C for 24 h. At the end of the heat curing process, the printed slabs were taken out from the oven and left in the laboratory to cool down to room temperature. All specimens were tested 7 days after printing in this study.

2.3 Testing

To investigate effect of wollastonite addition on the shape-retention-ability, the fresh mixture was filled into a cylindrical mold (60 mm in diameter × 60 mm in height), and the mold was subjected to a slight external vibration to compact the mixture adequately. The mold was then carefully and slowly lifted up. A circular steel plate (with a diameter of 60 mm and weight of 175 g) was placed slowly on the top surface of the fresh specimen. Before adding another steel plate, the fresh specimen was allowed to deform under the load of the previous steel plate for about 30 s. A digital camera was used to capture pictures of the fresh specimen before adding steel plates. The captured pictures were then imported into AutoCAD software to determine the change in height and width of the fresh specimen under the applied load.

To investigate effect of wollastonite addition on the yield stress evolution, following [8], the static yield stress of the fresh geopolymer mixture was determined based on measuring the penetration depth of a cone plunger (with a tip angle of 30°) in the fresh mixture. The cone plunger was allowed to penetrate into the fresh mixture under its self-weight and the penetration depth was measured every 5 min on the same fresh mixture at different spots until 60 min from the start of the measurement. It should be noted that additional weight was added on top of the cone plunger when the mixture was too ‘stiff’ to be penetrated by the original self-weight of the cone plunger. The static yield stress of the fresh mixture was determined based on the following equation [8]:

$$\tau_0 = \frac{m \times g \times \cos^2 \theta}{\pi h^2 \times \tan \theta} \quad (1)$$

where τ_0 , m , g , θ . and h are the yield stress (Pa), the mass of the cone plunger (kg), the gravity acceleration (m/s^2), tip angle of the cone plunger and penetration depth (m), respectively.

To determine the compressive strength and flexural strength of printed geopolymer, 30 mm cubic specimens and 30 mm $\times$ 30 mm $\times$ 160 mm prismatic specimens were extracted from the printed slabs. The compressive and flexural strengths of saw-cut

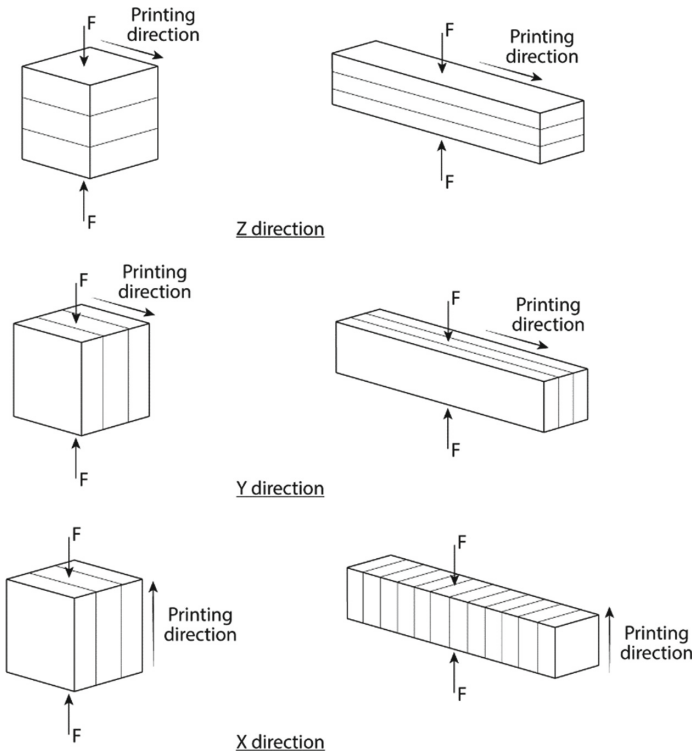


Fig. 1. Testing directions for compression and flexural tests of printed one-part geopolymer.

specimens were measured in X, Y and Z directions as shown in Fig. 1 The compressive strength of all cubic specimens was measured through uniaxial compression at a load rate of 20 MPa/min. The flexural strength of all prisms was measured in a three-point bending test setup with a 120 mm long span at the rate of 1.0 mm/min.

3 Results and Discussion

3.1 Shape-Retention-Ability

Figure 2 presents the shape-retention-ability results. It should be noted that the dimensional changes of the mixtures were recorded until the applied load was 4025 g, which is adequate to support the 1 m height of deposited layers without collapse [9]. As can be seen in this figure, the dimensional changes of M1 were significantly higher than those of M2 under the same applied load. The fresh specimen of M1 collapsed when the applied load was 3325 g, which is 9 times the self-weight of the fresh specimen (368 g). Immediately before collapse of the fresh specimen of M1, the final dimensional changes in the height and width of the fresh specimen were 10.4% and 3.9%, respectively. However, the fresh specimen of M2 did not collapse when the applied load was 4025 g, which is 11 times the self-weight of the fresh specimen. The final dimensional changes in the height and width of the fresh specimen of M2 under 4025 g of applied load were 5.7% and 3.0%, respectively. This excellent shape-retention-ability of M2 is due to addition of the needle-like wollastonite particles in the mixture which have mechanical interlock between each other and resist the deformation due to the applied stress on the fresh specimen.

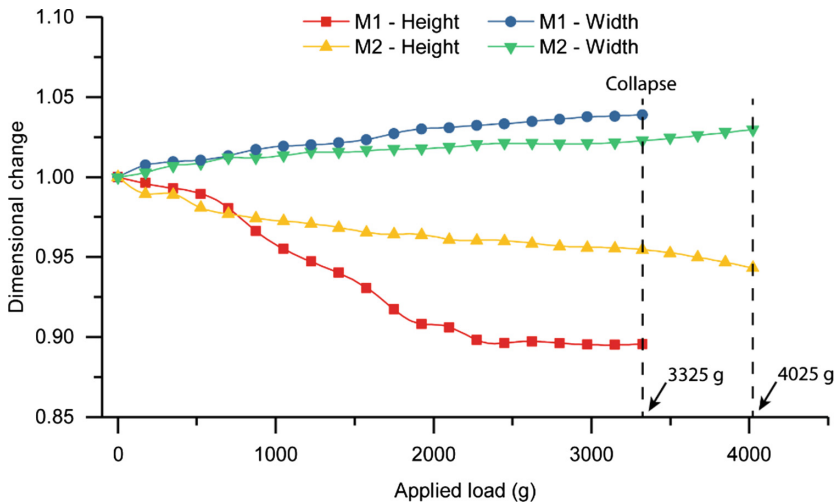


Fig. 2. Shape-retention-ability results. Note: Results of M1 adopted from Bong et al. [3].

3.2 Evolution of Static Yield Stress

Figure 3 shows the static yield stress evolution results. At each rest time, M2 had higher static yield stress than M1. The static yield stress evolution of both mixtures were exponentially increased over the rest time. It should be noted that the fit curves were in good agreement with Perrot et al. model [10]. As shown in Fig. 3, as the rest time increased, the difference between the static yield stress of M1 and M2 became more significant. The higher static yield stress of M2 could be mainly attributed to the overlap and mechanical interlock between needle-like wollastonite particles in that mixture. As the rest time becomes longer, some of the wollastonite particles may become partially dissolved in the alkaline medium, which in turn provides additional source of Si and Ca in the system [11]. The additional Ca in the system increases the rate of geopolymerisation process, and thus results in a more significant increase in the static yield stress of M2 [12].

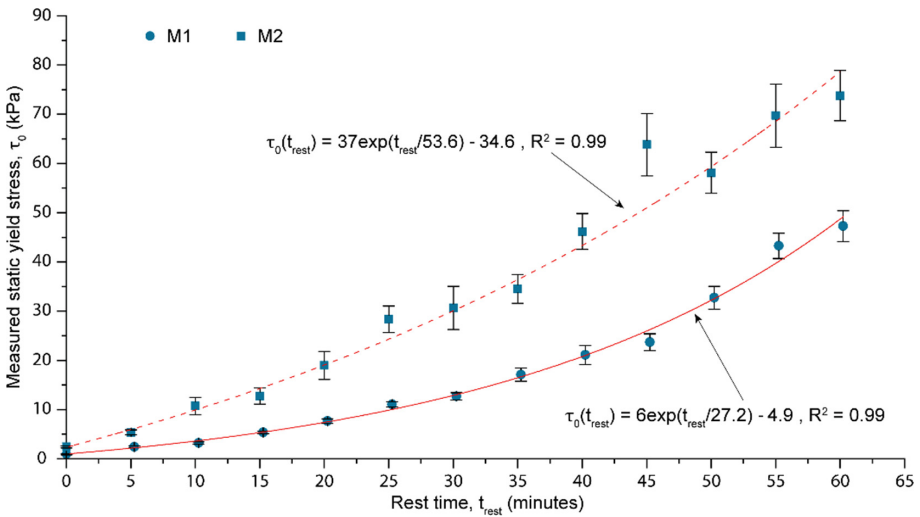


Fig. 3. Static yield stress evolution of each mixture. Note: Results of M1 adopted from Bong et al. [3].

3.3 Compressive Strength

Figure 4 presents the compressive strength results. The highest compressive strength was obtained in X direction (i.e. the printing direction), while the compressive strengths obtained in Y and Z directions were comparable. This pattern is true for both mixtures. The material was most likely compacted in X direction due to the pressure applied during the extrusion process, which led to achieving the highest compressive strength in this direction. As shown in Fig. 4, the compressive strengths of M1 and M2 were comparable, regardless of the loading direction. This indicated that the addition of wollastonite in the mixture had an insignificant influence on the compressive strength of the printed geopolymer.

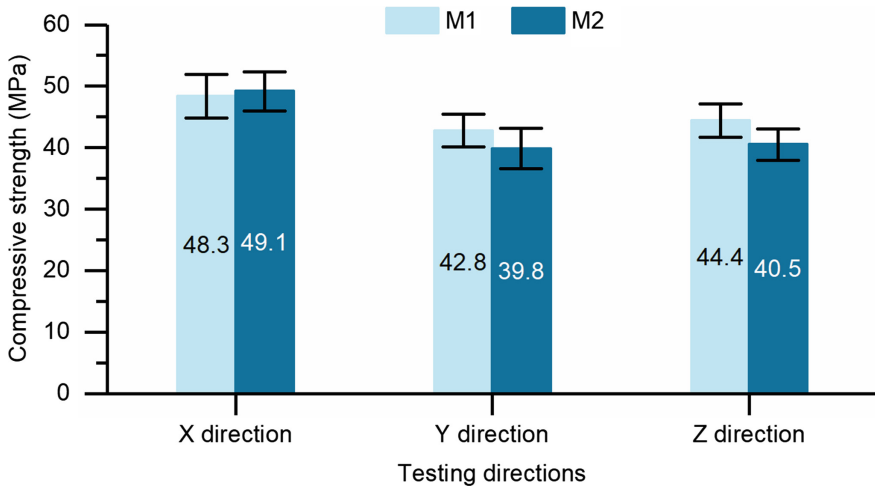


Fig. 4. Compressive strength of each mixture. Note: Results of M1 adopted from Bong et al. [3].

3.4 Flexural Strength

Figure 5 presents the flexural strength results. Similar to the compressive strength results, the flexural strengths of both mixtures also exhibited anisotropic behavior depending on the loading direction. The flexural strength in Z direction was more than that in Y direction. This is because the bottom layers of the printed specimen were compacted owing to the self-weight of the top layers [13]. The lowest flexural strength was in X direction as the applied load was parallel to the layers' interfaces, where the strength is greatly depended on the interlayer bond strength. The pattern obtained in terms of the testing direction is true for both mixtures.

As shown in Fig. 5, the flexural strength of M2 in Y and Z directions were 29% and 19% higher than those of M1. This is despite the fact that mixture M2 had higher water content than mixture M1 (see Table 1). However, the flexural strengths of M1 and M2 in X direction were comparable. The increase in the flexural strength of M2 is significant considering that only 10% of F-sand was replaced by wollastonite in this mixture. The higher flexural strength of M2 is attributed to the inclusion of the wollastonite particles in that mixture. The needle-like wollastonite particles partially dissolves in the alkaline solution and ultimately bonds to the geopolymeric gel, and thereby reinforces the geopolymer matrix and increases the flexural capacity of M2 [5, 11, 14].

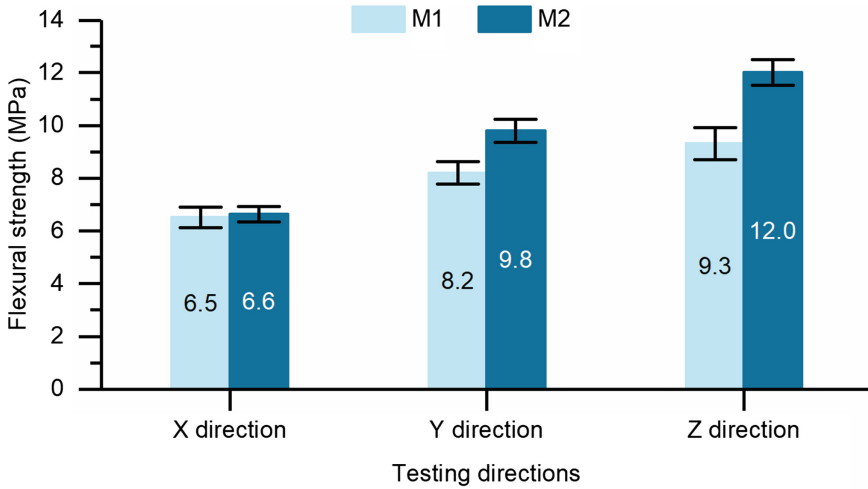


Fig. 5. Flexural strength of each mixture. Note: Results of M1 adopted from Bong et al. [3].

4 Conclusions

In this study the effect of wollastonite micro-fiber addition on the properties of a 3D-printable ‘one-part’ geopolymers was reported. Based on the experimental results, the following conclusions can be drawn:

- (1) Addition of wollastonite significantly enhanced the shape-retention-ability and yield stress evolution of the fresh geopolymer mixture.
- (2) Addition of wollastonite (10 wt%) significantly improved the flexural strength (up to 29%) in Y direction (i.e. parallel to the printing direction) and Z direction (i.e. perpendicular to the printing direction), while the flexural strength in X direction (i.e. loading parallel to the layers’ interfaces) remained unchanged.
- (3) Addition of wollastonite was found to have an insignificant effect on the compressive strength of the printed specimens. This is true irrespective of the loading direction.
- (4) The printed specimens exhibited anisotropic behavior in compression and flexure. This is true for both mixtures with and without wollastonite. In compression, the highest strength was in X direction, while the highest flexural strength was in Z direction.

Acknowledgements. Authors acknowledge the support by the Australian Research Council Linkage Infrastructure Grant LE170100168, and Discovery Early Career Researcher Grant DE180101587. Authors would like to acknowledge Building Products Supplies Pty Ltd (Subsidiary Business of Independent Cement and Lime Pty Ltd) for supplying the slag used in this study.

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Synthesis of Hybridized Rheological Modifiers for 3D Concrete Printing

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Abstract. Viscosity and static yield stress are key rheological properties for 3D concrete printing (3DCP), where high static yield stress is associated with high buildability and shape stability and low viscosity is associated with extrudability and pumping. The challenge in concrete rheology lies in decoupling the effect of admixtures on these two properties, i.e. achieving high static yield stresses while still maintaining moderately low viscosities. In this paper, we present a hybridized additive system of nanoclays and viscosity modifying admixtures that can tailor the rheological properties of cement composites to meet 3DCP performance requirements. Further, because 3DCP is a technology of scales, any additive must meet scalability and stability requirements for construction, i.e. ease of processing in abundance and relatively low cost, and exhibit an extended shelf life. We examine different methods of synthesizing the hybrid systems and examine their stability through measuring their effect on cement rheology at different component ratios and at different time stamps from the time of hybridization. We then demonstrate their impact on printing performance by producing complex 3D prints utilizing cement pastes modified with the hybridized additive system.

Keywords: Concrete 3D printing · Rheology · Synthesis · Nanoclay · Admixture

1 Introduction

Additive manufacturing is a recent technology that was first proposed for concrete under Contour Crafting by Khoshnevis [1] and later adopted by many researchers to previous applications. 3D concrete printing (3DCP) requires an unprecedented level of control of the rheological properties of cement composites, requiring a balance between high static yield stress for buildability and shape stability and low/moderate viscosity for extrudability and pumping [2]. To achieve rheological control, the use of admixtures will be key [3].

Static yield stress describes the material's resistance to flow and it is typically associated with a material's transition from solid to liquid. Viscosity, on the other hand, describes the material's resistance to flow under deformation and is associated with fluidity and pumpability. Cement colloidal forces via van der Waals and electrostatic

forces and early hydration, e.g. C-S-H bridging, have been identified to be the main interactions controlling such kinetics [4]. Thus, most rheological additives affect both static yield stress and viscosity proportionally, and achieving the high static yield stress desired for 3DCP can result in excessively viscous, un pumpable composites.

NC is one of few additives reported to increase static yield stress with minimal effect on viscosity due to its highly thixotropic nature [5–7]. However, because NC has relatively high water-adsorption, up to 200% according to [8], it has been reported that cement composites with high contents of NC exhibit low cohesion, resulting in voids and discontinuities in printed composites [9]. Such side effects prevent the higher contents of NC necessary to achieve target rheological properties for 3DCP when prepared conventionally.

While industries are keen to adopt 3DCP technology due to its disruptive potential, such complex rheological demand and high additive content remain as deterring challenges. In this study, we combine NC with a water soluble viscosity modifying admixture (VMA) to increase cohesion, increase static yield stress and improve overall printing performance of cement composites. We further examine different ways of synthesizing our hybrid system and test their efficiency after 1 week of producing the admixture.

2 Experimental Program

2.1 Materials

The NC used in this study are palygorskite or attapulgite clays supplied in highly purified powder form. They are 30 nm in diameter, 1.5–2.0 μm in length and carry a uniform negative charge along their length with positive charges at the ends [10]. The VMA used is a soluble low molecular weight cellulose ether supplied commercially in powder form. Cement is type I/II Portland cement and its chemical composition is shown in Table 1. The water to cement ratio (w/c) is kept at 0.34. Additions of NC and VMA are 0–2% by mass of cement are tested.

Table 1. Chemical composition of cement.

Content (%)						Loss on ignition (LOI)
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	
19.27	4.68	3.51	63	3.21	2.72	2.09

2.2 Material Processing

Both VMA and NC used in this study are supplied in powder form and can be added to the cement paste in either powder or solution form, where the latter is suspending or dissolving the material in water. To synthesize NC solution, magnetic stirring is one of the most commonly used methods and is suggested by the manufacturer [6, 10–12]. However, sonication remains the most common method to disperse nanomaterials, as it offers significantly higher energy than shear mixing. In this study, we compare all three

methods; mixing NC as powder with cement and producing NC solution by either magnetic stirring or sonication. When magnetic stirring is used, the solution is mixed at 500 rpm for 1 h. Sonication is performed using a sonicator probe at 300 Watts achieving 6,500 J/g of NC. On the other hand, a VMA solution can only be prepared via magnetically stirring the powder in high temperature water, then continuing stirring as the temperature drops to solubility levels.

To produce hybrids, we select magnetic stirring to prepare the NC solution and combine it with VMA via three methods. The first method, M1, is adding VMA as powder mixed with cement and adding NC in solution form. The other two methods M2 and M3 create hybrid solutions of both VMA and NC. In M2, two separate solutions are prepared and then the solutions are combined together. The resulting solution has half the original concentration of each of its constituents. For example, to prepare 1 wt.% NC with 1 wt.% VMA, two separate solutions of 2 wt.% NC and 2 wt.% VMA are prepared, then the NC solution is added and mixed in the VMA solution. In the third method, M3, both NC and VMA are added as powder to one solution creating one hybrid solution. Figure 1 summarizes all processes used in this study. We have previously tested the effect of adding VMA in powder and solution form to cement pastes and differences were found to be negligible on the rheological properties. However, such results are not included as they diverge from the scope of this paper.

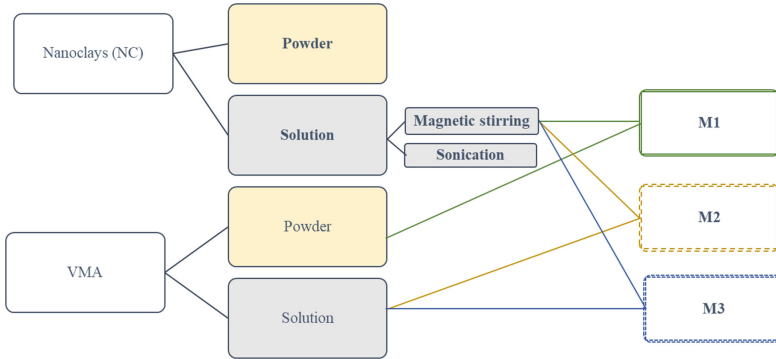


Fig. 1. Hybrid hierarchy chart based on different synthesis methods of NC and VMA additives.

2.3 Rheology

The vane and cup setup is used to measure the effect of the additives on the rheological properties of cement paste. The protocol for producing cement paste is kept consistent between all specimen and fresh paste is prepared for every test. A pre-shear at strain rate of 260 s^{-1} is applied for 1800 s to ensure all samples are at deflocculated state. At the end of the pre-shear, the steady-state viscosity is collected. A zero-stress condition is then applied for 300 s to allow structural build-up. A strain rate of 0.1 s^{-1} is applied afterwards to measure the static yield stress where the material transitions from solid to fluid. A minimum of 3 tests are performed and averaged to quantify the rheological properties. All tests are performed at 25°C .

2.4 Stability

In order to examine the shelf-life effect of our hybrid system we test the static yield stress immediately after synthesis of the hybrid solution or dispersion of NC in solution, as well as exactly 1 week after (168 h). Solutions are kept covered in controlled lab conditions (24 °C) with minimal handling. Similar mixing and rheological protocols are used for both specimens.

2.5 3D-Printing



Fig. 2. Gantry system used with capacity of 60 cc using syringe and plunger setup

A 60 mL syringe gantry 3D printer, shown in Fig. 2, is used to produce prints with cement paste incorporating the hybrid additive system described in this work with a 14 gauge dispensing straight stainless steel needle with an inner diameter of 1.6 mm. Printing layer height varies based on geometry and is in the range of 0.8 mm to 1.5 mm. The gantry speed is set to 800 mm/min during printing and a plunger is used to apply force for extrusion. The gantry system has a printing area of 250 mm 250 mm and vertical height of 100 mm. Printing codes are either manually generated or automatically using commercially available software; Simplify3D.

3 Results

To study the effect of combining VMA with NC on cement paste rheology, NC contents of 0.1, 0.5, 1.0 and 1.5 wt.% are tested with VMA contents of 0, 1.0 and 2.0 wt.%. For this investigation, the simplest hybridization method of adding NC as solution and VMA as powder (referred to as M1 in Fig. 1) is selected. We then select 1 wt.% NC and 1 wt.% NC + 1 wt.% VMA to examine the influence of different dispersion/hybridization methods; M1, M2 and M3 and measure static yield stress right after solution synthesis and again exactly 1 week (168 h) after to measure stability. Finally, we show some examples of 3D printed shapes using the hybrid system.

3.1 Rheological Properties

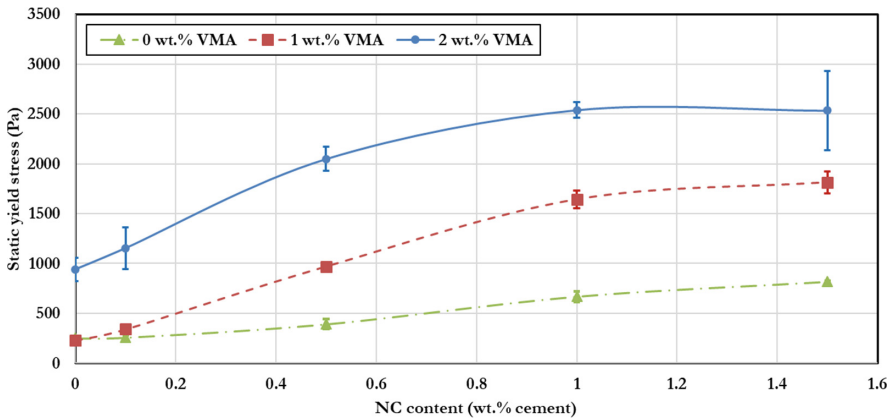


Fig. 3. Static yield stress results at varying contents of NC and VMA

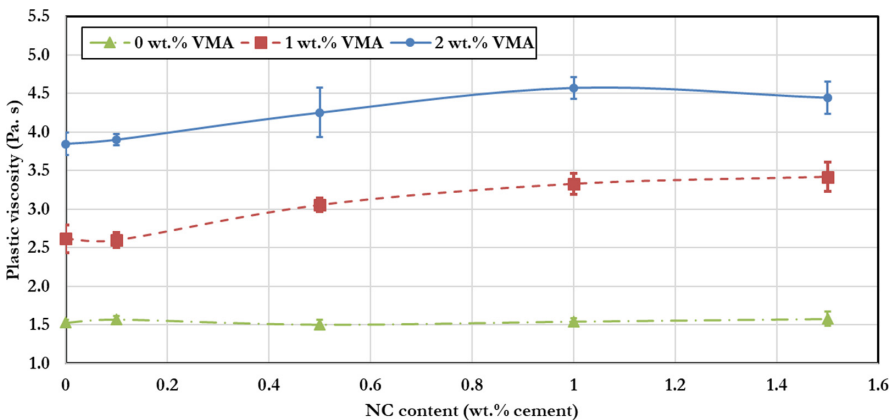


Fig. 4. Steady-state/plastic viscosity results at varying contents of NC and VMA

Figure 3 presents the results of static yield stress, where the result of NC without any VMA is shown in the dashed-dot line with triangles. As expected, we observe an increase in static yield stress with increase in NC content – up to 228% at 1.5 wt.% NC compared with the plain paste. It is also apparent that without NC, 1 wt.% VMA leads to no measurable change, while 2 wt.% VMA increases static yield stress by 280% compared with the plain paste. Combining both NC and VMA increases the static yield stress further – up to 628% and 918% with the combination of 1.0 wt.% VMA + 1.5 wt.% NC and 2.0 wt.% VMA + 1 and 1.5 wt.% NC, respectively.

The addition of VMA to cement paste results in an increase in viscosity proportional to VMA content, as shown in Fig. 4, and is associated with higher VMA

interactions. On the other hand, addition of NC alone does not notably alter the viscosity of cement paste up to 1.5 wt.% content. Nevertheless, it is important to highlight that even the highest increase in viscosity of 300% at 1.0 wt% NC with 2.0 wt.% VMA, the corresponding increase in static yield is almost an order of magnitude higher than plain paste at 918%. We further show that such viscosities are still suitable for pumpability and extrudability later in Sect. 4, where pastes incorporating 1 wt.% NC and 1 wt% VMA with a viscosity of 3.35 Pa.s are printed.

The increase in static yield stress of all hybrid mixes can be attributed to an increase in effectiveness of NC interactions, VMA interactions or new interactions between NC and VMA. Since changes in NC content does not affect viscosity while increasing VMA content increases viscosity, the change in viscosity can be associated with proportional change in VMA interactions. Comparing the change in static yield stress in Fig. 3 from 1 to 1.5 wt.% NC at 0, 1 and 2 wt.% VMA, there is less increase in static yield stress with increasing VMA content until no increase is observed at 2.0 wt.%. Similar behavior is observed for viscosity, shown in Fig. 4. Thus, increased VMA interactions can critically increase the static yield stress. However, since 1.0 wt.% VMA alone shows no change in static yield stress from the reference, there must be a critical concentration of VMA to enable such effects. Further investigation is required to characterize the changes in NC interactions and the new VMA-NC interactions.

3.2 Stability

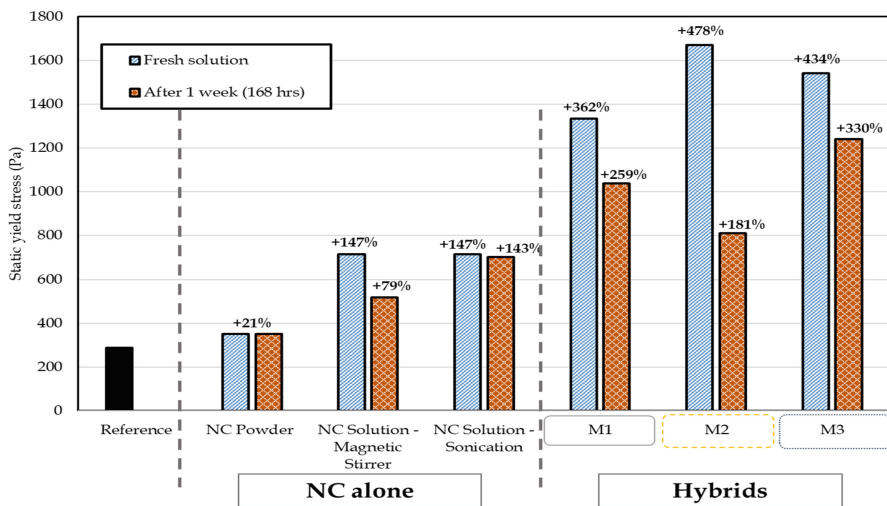


Fig. 5. The static yield stress of cement paste containing either NC or hybrid NC and VMA additives at 1 wt.% NC or 1 wt.% NC and 1 wt.% VMA.

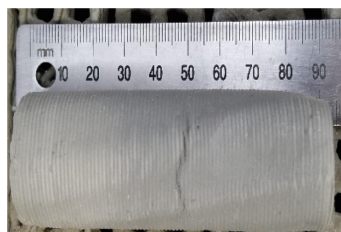
The static yield stress of cement pastes prepared with 1 wt.% NC alone and a hybrid of 1 wt.% NC + 1 wt.% VMA using three dispersion/hybridization methods are compared. The results of static yield stress measured immediately after solution preparation

and exactly 1 week after are summarized in Fig. 5. Mixing in NC as powder does not show any decay in performance, as there are no issues with stability with powders. However, as-received, dry NC will be aggregated and thereby not well dispersed in the cement paste, which explains the moderate 21% increase in static yield stress. In contrast, both magnetic stirring and sonication significantly improve NC efficiency and offer similar responses immediately after dispersion, leading to a 147% increase in static yield stress compared to the reference. However, after 1 week of preparing NC solutions, the dispersive state of NC using magnetic stirring decays, losing half of its effectiveness, while sonication maintains a similar performance after 1 week, indicating it remains well-dispersed in solution.

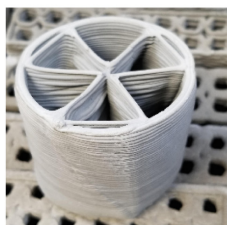
Since magnetic stirring shows a decay in performance and is one the most common methods used for NC in literature, we utilize it in examining the three hybridization methods, as discussed in Sect. 2.2. In the fresh solution state, M2 offers the highest increase in static yield stress. However, this method goes on to exhibit the largest loss of efficiency at 62% after 1 week. Because M2 combines two separate solutions to synthesize a new hybrid one, each constituent solution has higher content of additive in its original state. That is, to produce 1 wt.% NC and 1 wt.% VMA hybrid solution in M2, the constituent solutions each has 2 wt.% NC and 2 wt.% VMA. Maintaining dispersion at higher nanomaterials content is harder and the decay in dispersion of NC is worsened. Hybrid solutions via hybrid synthesis (M3) on the other hand show significantly higher stability, indicating that solubilizing VMA when NC is in the well dispersed state not only significantly drives static yield stress but further improves the stability of NC dispersion. This is evident when comparing the loss of 24% of M3 compared to 48% with NC dispersed via magnetic stirring. Finally, combining NC solution with VMA powder (M1) seems to offer a median performance both as a fresh solution and after 1 week. This method is the most suitable for scaling for industrial use as it utilizes the lowest energy, ease of processing and offer rheological properties suitable for 3DCP processes. If longer shelf-life is required, NC solutions prepared via sonication show no loss of performance after 1 week; we contemplate that M1 method of synthesis utilizing sonication can actually result in the highest stability and highest performance after 1 week; such can be another attractive method for industrial use but would require initial investment in equipment.

4 Printing Performance

The printing performance of our proposed hybrid system is demonstrated here through a buildability test and producing multiple complex items, as shown in Fig. 6. 1 wt.% NC with 1 wt.% VMA is chosen following M1 hybridization, as it represents median viscosity and static yield stress. Buildability is assessed through measuring the maximum achievable height before deformation, where deformation is caused by insufficient rheological properties and not by structural instability such as buckling or thin walls. The result shown in Fig. 6a achieves a maximum height of 92 mm using 1.2 mm layer thickness. (The buildability test must be stopped after 92 mm as that is the maximum height of the gantry system and maximum volume of the syringe.) To

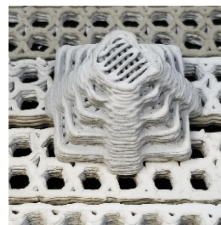


(a) Buildability test achieving over 90mm height



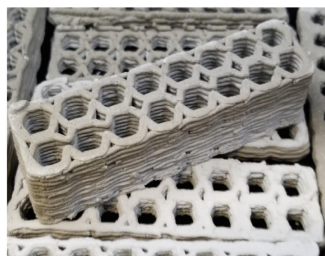
(b) Cylinder with braced internal infill

- Diameter = 54mm
- Height = 56 mm



(c) Rectilinear infill for Mayan pyramid

- Width = 49mm
- Height = 26mm



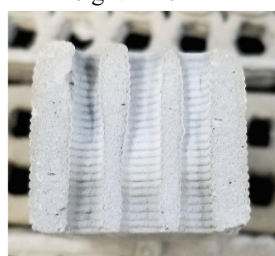
(d) Honeycomb infill prisms

- Width = 27mm
- Length = 102 mm
- Thickness = 22mm



(e) Shell structure by a rotating hypocycloid

- OD = 59 mm
- Height = 50mm



(f) Internal structure of 3D printed sample broken in half

Fig. 6. 3D print examples utilizing hybrid system at 1 wt.% NC and 1 wt.% VMA showing different complex geometries.

prevent thin wall collapse, the cylinder used in buildability has similar internal structure as the enlarged cylinder shown in Fig. 6b.

Figure 6c shows a miniature of a Mayan pyramid prepared using Simplify3D to demonstrate the applicability of commercial 3D printing software. Figure 6d shows an example of honeycomb infill pattern producing prisms suitable for flexural testing while Fig. 6e shows an example of a continuously rotating structure with layer height. It is important to note that the vertical component of many of these prints are limited due to the limited volume of the syringe printer used. Finally, Fig. 6f exposes the cross-section of prints, showing no signs of striation internally as evidence of good bonding in this printing scheme.

While not shown here, printing with NC system alone often results in clogging of the syringe due to segregation resulting in water bleeding. We acknowledge that such effects are due to the nature of the syringe extrusion system, which creates an uneven pressure profile within the syringe. However, such problems are uncommon in this study when utilizing the hybrid system. These results suggest that NC alone, despite having high static yield, may not be sufficient for syringe-based 3DCP. However, the influence of these admixtures systems on different printing systems, e.g. progressive cavity pump, still needs to be investigated as the shear history would be very different.

5 Conclusion

In this work, we propose a new hybrid additive system using nanoclays and VMA. We show that the hybrid system significantly outperforms NC or VMA alone in increasing the static yield stress, reaching almost an order of magnitude increase from the reference cement paste – 918% increase with 1 wt.% NC with 2 wt.% VMA. We also show that while utilizing the VMA there is an increase in viscosity, although the increase is not proportional to the increase in static yield stress. Further, during 3D printing the use of VMA increases printing ink cohesion, reducing clogging and gaps in the print, as opposed to using NC alone. We also look at the stability of dispersed/synthesized solutions, comparing static yield stress using freshly prepared solutions versus week old solutions. Results show a decay in performance except when mixing NC as dry powder or when using sonication. While a decay in performance is observed in all hybrid mixes, it is essential to highlight that regardless of the method of synthesis, all hybrid mixes significantly outperform 1 wt.% NC alone, even after decay. The proposed hybrid system is used to produce a number of complex prints showing high level of control over the rheological properties, translating to high buildability, shape stability, extrudability and detail. The method of hybridization we suggest is to prepare NC solution via magnetic stirring or sonication and combine it with VMA, where the VMA is premixed in powder form with cement.

Acknowledgements. The authors would like to acknowledge the National Science Foundation (Award # 1653419) for financial support, and technical support by the staff of Columbia University's Carleton Laboratory. We would also like to acknowledge the efforts of Hajin Kim, Elise Westhoff, Jonathan Rosas and Jithu Alexander for contributing to our experimental procedures and testing.

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Control of Strand Properties Produced with Shotcrete 3D Printing by Accelerator Dosage and Process Parameters

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Abstract. Shotcrete 3D Printing (SC3DP) has recently evolved as a large-scale additive manufacturing technique. The major advantage of this technique is the high manufacturing speed for creating large-sized monolithic structures. However, to control this technique properly, the combined effects of process parameters and rheological properties of the concrete need to be fully understood. Therefore, the effect of accelerator dosage (0%, 2%, 4%, 6%) on the material's yield stress is quantified with a penetrometer up to 90 min after deposition. The vertical deformation of strands is also found to correlate with yield stress. Moreover, the resulting geometry of the strands is analyzed. Here, an increase in strand height and a decrease in strand width is determined with increasing accelerator dosage. Among other factors, this is deduced to the opening angle when material leaves the nozzle. To compensate unwanted changes in geometry due to accelerator, process parameters to modify the geometry are studied as well. Therefore, the effect of traverse speed, nozzle-to-strand-distance and volume air flow on the geometry is quantified.

Finally, the possibilities to use the findings of the effect of accelerator dosage and process parameters during printing process purposefully are discussed.

Keywords: Shotcrete 3D printing · Admixtures · Accelerator · Process parameters · Strand geometry

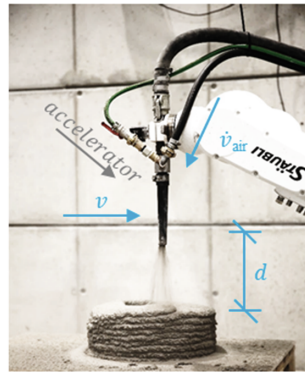
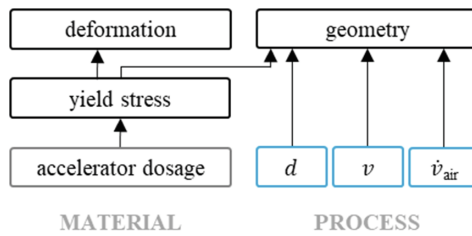
1 Introduction

3D printing of concrete recently became one of the emerging technologies in concrete construction [1–8]. In particular, extrusion and Shotcrete 3D Printing (SC3DP) evolved as large-scale additive manufacturing techniques [9–11]. Unlike the extrusion method, SC3DP uses high kinetic energy for the application of concrete. Similar to extrusion-deposition techniques, the premixed fresh materials are conveyed to the print head while pumping. However, at the nozzle the material is torn up by pressurized air and sprayed at the substrate (previous fresh concrete layer, formwork or hardened concrete). Specimens manufactured with this technology show an increase of contact surface between the printed layers, which allow a good interlocking effect [12]. In general, the major advantage of the deposition-techniques is the high manufacturing speed for creating large-sized, free formed monolithic structures. These building

components are produced automatically and directly from a digital model without human intervention. Herewith, this technique enables saving materials' wastage, construction time and labor.

Although this rather new construction technique shows many advantages, also some dualities compared to traditional casting of concrete have to be addressed. This is mainly caused by the pumping process and the required pumpability on the one hand and the subsequent rapid structural build-up as well as pursued interlayer strength on the other hand [12–14]. To meet these requirements, the targeted use of admixtures such as set accelerator added at the nozzle, is necessary. However, this affects the geometry of the produced strands. To reach the target geometry of strands, also process parameters (e.g. nozzle-to-strand-distance, traverse speed, volume air flow) may be varied. Therefore, profound understanding of material-process-interactions is required. This allows to adapt material and process to the specific requirements and facilitates offline path planning.

Therefore, in the following the effect of accelerator dosage on yield stress and geometry as well as the effect of the process parameters traverse speed, volume air flow and nozzle-to-strand distance on geometry are investigated, Fig. 1.



v : traverse speed
 d : nozzle-to-strand-distance
 $\dot{v}_{\text{air}}$: volume air flow

Fig. 1. Picture of a robotic arm and parameters investigated to quantify the effect of accelerator and process parameters on strand properties in SC3DP (photo: Institute of Structural Design, TU Braunschweig).

2 Materials and Methods

2.1 Material

The mixture composition of the material used in the presented experiments is given in Table 1. The mixture encompasses Ordinary Portland Cement, aggregates with a maximum grain size of 3.15 mm, ground limestone, water, stabilizer and superplasticizer. Various amounts of accelerator (0, 2, 4 and 6% bwoc) are added to the premixed material at the nozzle.

Table 1. Mixture composition for the used fine grain concrete.

Components	Value	Unit
Portland cement (CEM I 52.5)	600	kg/m ³
Ground limestone	97	kg/m ³
Aggregate, d = 0–3.15 mm	1258	kg/m ³
Water	270	kg/m ³
Stabilizer	0.1	M.-%
PCE superplasticizer	0.3	% bwoc
Alkali-free set accelerator	0–6	% bwoc

2.2 Methods

Production of Specimen and Testing Program. For material processing, a small lab-scale SC3DP unit is used (Smart Additive Manufacturing Material Investigator - SAMMI), Fig. 2. SAMMI contains a x-z-linear axis with a default traverse speed of 4500 mm/min. The shotcrete material is produced outside of the working space with a pug mill mixer (Mader WM Jetmix 125/180) and pumped (Mader WM Variojet FU) with a discharge rate of 0.8 m³/h through a 5 m long rubber hose (diameter 35 mm) to a shotcrete nozzle. There, pressurized air (volume air flow: 25–45 m³/h) and – if applicable – accelerator is added. A working distance between nozzle and specimen of 10–30 cm is used. For the presented experiments, each setting encompasses three stacked 120 cm long strands.

To quantify the effect of accelerator on strand properties (yield stress, vertical deformation under loading as well as geometry) various dosages are added at the nozzle at a volume air flow of 45 m³/h and a nozzle-to-strand distance of 20 cm:

- 0%,
- 2%,
- 4%,
- 6% accelerator.

In order to investigate the effect of different process parameters on the resulting strand geometry, the following parameters are varied:

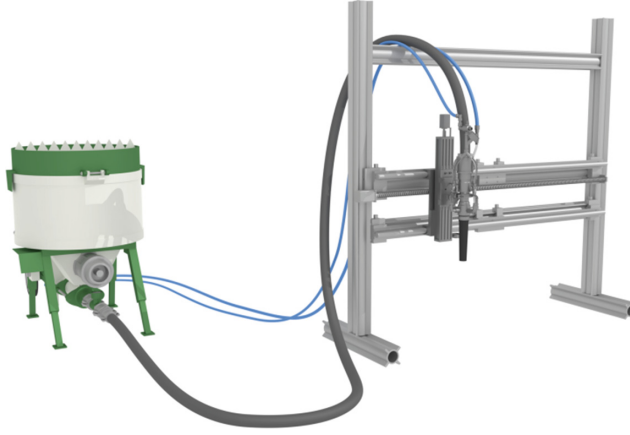


Fig. 2. Smart additive manufacturing material investigator (SAMMI) to produce Shotcrete 3D printed strands [11].

- Traverse speed: 3500 mm/min and 4500 mm/min with volume air flow = 45 m³/h and nozzle to strand distance = 20 cm.
- Volume air flow: 25, 35, 40, 45 m³/h with traverse speed = 4500 mm/min and nozzle to strand distance = 20 cm.
- Nozzle to strand distance: 10, 20, 30 cm for a traverse speed = 4500 mm/min and volume air flow = 25 m³/h.

Penetration Resistance and Yield Stress. To discontinuously investigate the penetration resistance evolution of sprayed concrete, a shotcrete penetrometer (Mecmesin) is used from 5 to 90 min after deposition. According to [15, 16] penetration resistance is correlated to yield stress of cement paste and mortar when a sufficiently large needle is used (used needle has a radius $R = 1.5$ mm, a cylindrical height $h_1 = 12.5$ mm, cone height $h_2 = 2.5$ mm). Herewith, (approximated) yield stress is determined according to [15] with:

$$\tau_0 = \left(\pi R (R^2 h_2^2)^{1/2} + 2\pi R h_1 \right)^{-1} F \quad (1)$$

For each point in time, five repetitions are conducted in the centre of the specimen.

Expansion Angle During Production and Geometry of the Strands. The expansion angle α from the nozzle is qualitatively determined using a high-speed camera at 7750 fps (MS55K, mega speed USA), Fig. 3. The height and width of every layer is measured with a ruler after deposition.

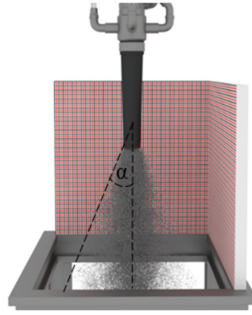


Fig. 3. High-speed imaging setup with indicated expansion angle.

Vertical Deformation Under Mechanical Loading. In order to quantify the vertical deformation of the manufactured strands with various accelerator dosages, two 30 cm long segments from the produced specimen are used. Each of the segments consists of three stacked layers. Load is applied 10 min after deposition in a testing machine (Zwick/Roell Z020) with a testing speed of 2 N/s up to a force of 1000 N to simulate the additional load when applying approximately 50 additional layers. The load is applied to the specimen over a length of 20 cm and is recalculated to stress over the loaded width of the strand. With an optical measuring system (Aramis, GOM, Braunschweig, Germany) the deformation of the first layer is quantified. The setting for load application are representative for a typical printing progress to produce a wall with a height of approximately 1.5 m within 10 min. Each specimen is pre-loaded with 40 N to ensure a constant load introduction. During loading, the deformation at the interface between the bottom strand and the second strand is recorded.

3 Results and Discussion

3.1 Effect of Accelerator Dosage

Yield Stress Evolution. An increase in yield stress over time is observed for all strands produced by SC3DP, Fig. 4. As expected, an increase in accelerator dosage from 0% to 6% leads to an increase of initial yield stress as well as slope of the yield stress evolution. After 90 min the yield stress of the specimen with 6% accelerator (1710 kPa) is approximately 15 times higher than the yield stress of the sprayed layers without accelerator (111 kPa). As expected, the accelerator provides rapid stiffening of the concrete.

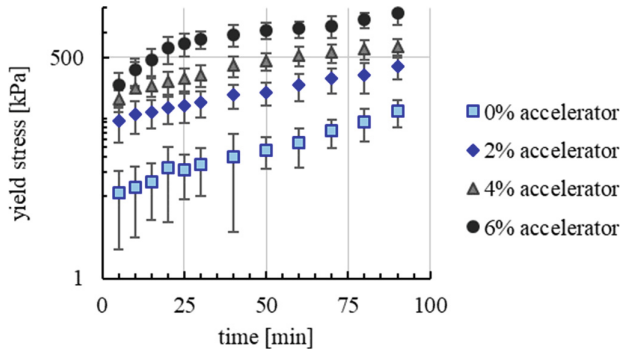


Fig. 4. Yield stress evolution over time after deposition of SC3DP-strands containing 0%, 2%, 4% and 6% of accelerator. Strands produced with 4500 mm/min traverse speed and 45 m³/h volume air flow, yield stress data from [11].

Vertical Deformation Under Loading. Since the loaded samples have varying geometries (see below), the force increase is converted into a stress increase with the help of the measured geometry of the strands. A clear correlation is observed between the accelerator dosage and the vertical deformation under loading of the printed layers, Fig. 5 (from [11]).

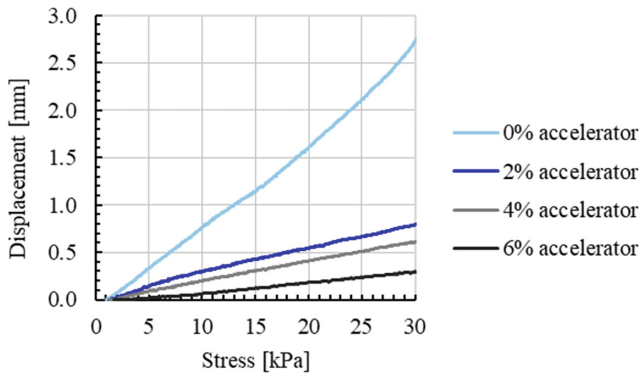


Fig. 5. Displacement-stress-curve measured at the interface between bottom layer and second layer at various dosages of accelerator 10 min after concrete deposition (traverse speed: 4500 mm/min, air flow: 45 m³/h), from [11].

Particularly distinct is the step from no accelerator (2.7 mm) to 2% accelerator (0.8 mm), which is accompanied by an absolute displacement difference of approximately 2 mm at a stress level of 30 kPa. The lowest vertical displacement is reached for 6% accelerator, with a vertical displacement of 0.3 mm for 30 kPa. Therefore, it can be

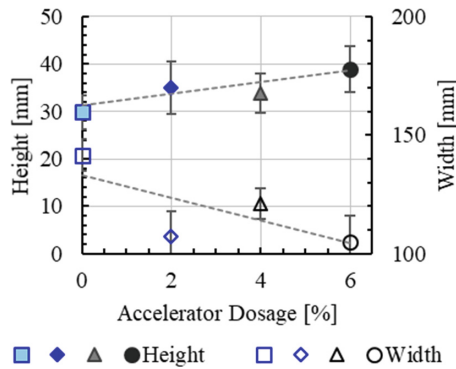


Fig. 6. Geometry of the strands containing various dosages of accelerator (traverse speed: 4500 mm/min, air flow: 45 m³/h).

stated that rather low accelerator dosages lead to a significant reduction in material deformation. Thus, a faster vertical building progress is achievable.

Geometry. An increase in strand height is observed when adding accelerator, Fig. 6. When increasing accelerator dosage from 0% to 6%, an increase in strand height from approximately 30 mm to 40 mm is measured. At the same time, the width of the specimen decreases. This is deduced to a) a reduced expansion angle if accelerator is added at the nozzle, which has been observed by high speed imaging, Fig. 7 and b) a lower tendency for deformation due to higher yield stress, Fig. 4.

3.2 Effect of Process Parameters

Nozzle to Strand Distance. When increasing the nozzle to strand-distance a linear increase in strand width and a decrease in strand height is observed, Fig. 8. When changing the nozzle-to-strand distance from 10 to 30 cm, a decrease in strand height from 33 to 28 mm is observed, which corresponds with a decrease of approximately 15%. The volume remains constant. The change in geometry is mainly deduced to the larger diameter of the jet spray, when increasing the nozzle-to-strand-distance.

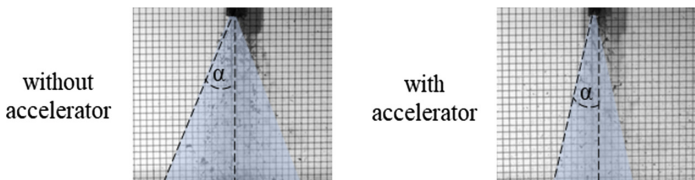


Fig. 7. Expansion angle when material leaves the nozzle without (left) and with accelerator (right).

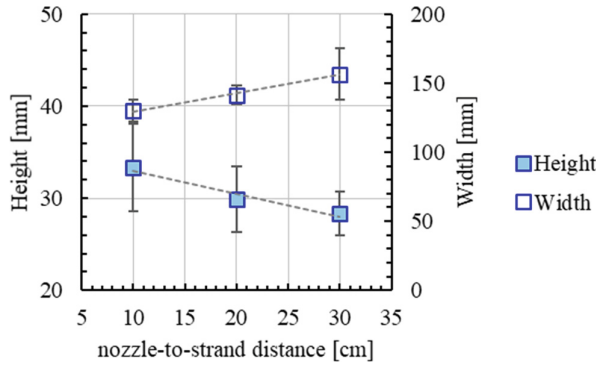


Fig. 8. Effect of nozzle-to-strand-distance on height and width of strands containing no accelerator (traverse speed: 4500 mm/min, air flow: 45 m³/h).

Volume Air Flow. When increasing volume air flow, no distinct change in strand height is observed, Fig. 9. Only a marginally change in height is possible, whereas the width increases slightly more. In order to investigate this effect in more detail, further experiments are required. However, volume air flow is not a main influencing factor within the investigated boundary conditions regarding the geometric properties of the applied strands. It needs to be mentioned that volume air flow tears the concrete in the nozzle. Herewith a high contact surface area between concrete and air stream is accompanied, which is prerequisite for an appropriate intermixing of admixtures added at the nozzle. Therefore, higher volume air flows are usually preferred.

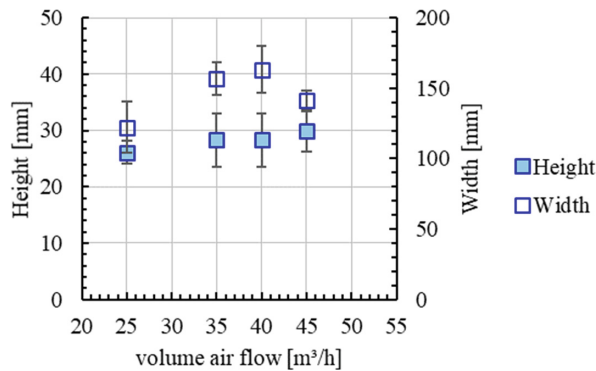


Fig. 9. Effect of volume air flow on height and width of strands containing no accelerator (traverse speed: 4500 mm/min, nozzle distance: 20 cm).

Traverse Speed. When increasing the traverse speed from 3500 mm/min to 4500 mm/min, the strand height and width decreases, Fig. 10. With a reduction of more than one 30%, the height decreases proportionally more than the width, which

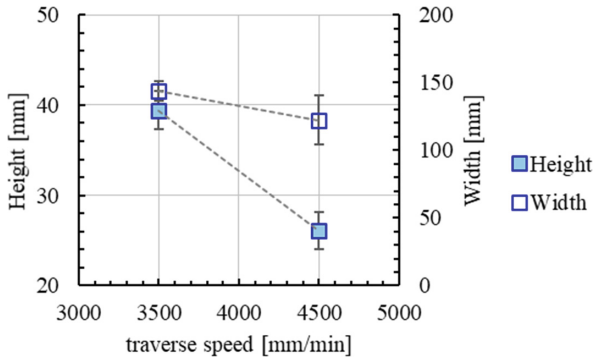


Fig. 10. The effect of traverse speed on height and width of strands containing no accelerator (volume air flow: 25 m³/h, nozzle-to-strand-distance: 20 cm).

decreases by 15%. A reduced volume per running meter is applied. The height decrease is explained by a shorter residence time of the nozzle over the strand when the traverse speed is high. Moreover, a high velocity of the material application in SC3DP-technique is prevalent. This additional mechanical loading leads to a permanent deformation of the strand. When traverse speed is reduced and the “application load” duration increases, an increased strand width is observed.

4 Summary and Outlook

One main challenge of automation is to understand and redefine the concrete spraying process with all its interdependent parameters. Therefore, the effect of accelerator dosage (0%, 2%, 4%, 6%) and process parameters on strand properties produced with Shotcrete 3D Printing technology was investigated in this research. Besides accelerator dosage, the mixture composition was kept the same during all the experiments. The following conclusions can be drawn for fine grain concrete when adding accelerator:

- A severe increase in initial yield stress and in yield stress evolution over time is observed, which enables higher vertical building rates.
- Vertical deformation under mechanical loading is reduced significantly.
- An increase in strand height and a decrease in strand width is observed.

When changing process parameters (traverse speed, volume air flow and nozzle-to-strand-distance) in the production process, the geometry of the strand is affected as follows:

- An increase in nozzle-to-strand-distance enables broader and more flat strands.
- In the investigated range, volume air flow does not affect the strand geometry significantly.
- An increase in traverse speed leads to a decrease in strand height and width.

To fully exploit the potential of Shotcrete 3D Printing in terms of geometric precision, a deeper understanding of material-process interaction is needed. Geometric conformity with the designed shape is indispensable to gain a commercial viability in the future. To utilize the capabilities of the presented technique further investigations will comprise a systematic investigation of deformation of placed material and finishing techniques. These will encompass for example application of additional thin layers or robot assisted post-processing techniques. A further development of design methods as well as process and material control is aimed to achieve. These topics will be addressed in future research.

Funding. Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project-ID 414265976 – TRR 277.

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Comparison of Printable Inorganic Binders - Key Properties for 3D Printable Materials

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Abstract. Four 3D printable Portland cement-based mix designs were developed. A method for determination of compressive and flexural strength of 3D printed prisms (taking into account the effects of 3D printing on the surface of the object) and a comparison to molded samples are presented. Prisms prepared by 3D printing show interfilament voids but have nevertheless mean values of compressive strength which are comparable to molded prisms. Flexural strength was strongly affected by surface irregularities introduced by manufacturing by 3D printing and is in every case lower as for molded specimens. In most cases, the variation of strength values of 3D printed test specimens was considerably higher than for molded equivalents. The presented Portland cement-based mix designs include a mix with the use of an ordinary Portland cement (OPC) clinker mixed with a calcium sulfate addition which is lower than in standard OPC which was also successfully utilized for 3D printing. This mix performed best in compressive and flexural strength. The developed materials were further examined by slump test and ultrasonic wave velocity.

Keywords: 3D printing · Portland cement · Standard test · Compressive strength · Ultrasound velocity · Sulfate carrier

Freeform additive manufacturing (AM) or 3D printing describes the automated construction of components by depositing single layers of material on top of each other. In the construction industry, AM is an emerging technique and several different concepts of 3D printers have already been presented [1]. According to Labonnote et al. [2], extrusion-based AM is by far the most investigated class of AM in construction and the present publication also focuses on this approach. Several publications [3, 4] already addressed the challenges arising when a cement paste, which is time-dependent changing its properties, becomes automatically deposited without the use of any formwork. These challenges comprise for example of the decrease of the ease with which the material is being delivered through the printing system (referred to as extrudability) over time, as well as the introduction of anisotropic properties into the printed component [5]. Because of these influences of the manufacturing process, no standardized or at least common method has been implemented to test the properties like flexural and compressive strength of 3D printed objects up to now. Hambach and Volkmer [6] examined strength values but did not compare them to molded samples. Le et al. [7] examined samples cut from 3D printed objects which do not account for

the surface irregularities of 3D printed objects. In the present study, a printing path to print prisms with parameters close to those of EN 196-1 [8] is proposed and their compressive and flexural strength were compared with molded prisms.

Four mix designs for 3D printable mortars are presented. The goal was to find comparatively simple compositions, especially with a small number of admixtures in comparison to published mixtures [9]. Also, the acceleration of initial strength gain was targeted for the study. There are three ways to achieve a faster setting of Portland cement-based 3D printing materials: first use of accelerators/admixtures [9, 10], second addition of aluminate cements and third use of ordinary Portland cement (OPC) clinker mixed with a calcium sulfate addition which is lower as in standard OPC [11, 12]. The current mixtures include only the last of the aforementioned types. The found printable compositions were examined further by slump test and ultrasound pulse velocity.

1 Materials and Methods

1.1 Binders and Mortar Design

A total of 4 printable materials was designed (Table 1). During the material development, the extrudability and the buildability of the materials were optimized to achieve continuous filaments which sustain their own weight and the weight of the layers above up to the building height of the printed prisms.

Table 1. Mixture design of 3D printable mortars (all quantities in grams).

Sample name	CEM	CEM+BS+LS	CEM+LS	CEM-S
CEM I 52.5 R	700	350	350	–
Clinker plus sulfate ^a	–	–	–	700
GGBS ^b	–	210	–	–
Limestone powder	–	140	350	–
Fly ash	200	200	200	200
Silica fume	100	100	100	100
Sand	1000	1000	1000	1000
Superplasticizer	7	7	7	7
Water	260	270	260	255
w/b	0.26	0.27	0.26	0.255

^aOPC clinker mixed with a calcium sulfate addition lower as in common OPC

^bGround granulated blast furnace slag

The basic material (sample name CEM) was based on a mix design presented by Le et al. in 2012 [3]. The particle size range of the sand should be 0–0.5 mm to ensure continuous material extrusion. ViscoCrete-2014 from SIKA Deutschland GmbH was used as a superplasticizer. In the other mixes, the CEM I 52.5 was partially or fully replaced by ground granulated blast furnace slag, limestone powder or a cement with

reduced sulfate carrier. The latter was prepared by mixing ground OPC clinker (from which also the CEM I 52.5 is produced) and ground natural anhydrite. The added anhydrite was equal to an SO_3 addition of 0.4% by weight of clinker.

1.2 Printed Prisms

Printing of mortar prisms was done with a paste extruder printer of own construction, which will be described in detail elsewhere [13]. It was specially designed for printing complex structures with the need to control, change and stop the material flow instantly. The material for 2–3 prisms was mixed in a single batch, deaerated and stored in the printer's reservoir. The extrusion nozzle had a diameter of 6 mm.

The extrusion rate was at maximum speed 100 mL/min and in average 40 mL/min. The printing was done in layer-by-layer mode. The path of the layers is further described by Fig. 1. The uppermost layer was designed to be printed parallel to the width of the prism to simulate the worst case for failure path relative to the 3D printing-introduced surface irregularities of the object.

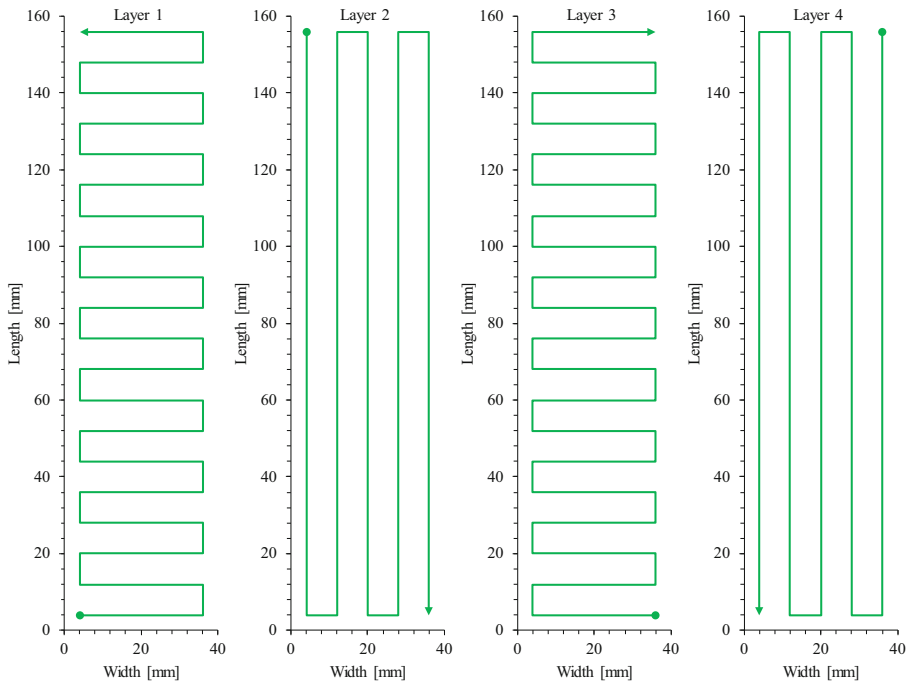


Fig. 1. Representative parts of the printing path for a prism. Circles indicate the start of a layer, the arrow the end. The printing continues with repeating these patterns for the next layers (layer 5 has an identical pattern as layer 1, layer 6 as layer 2, ...). The width of the deposited string is 8 mm, and there are 11 layers in the height to give a prism with approximately standard measurements of 160 mm • 40 mm • 40 mm.

After printing, the prisms were cured for 24 h at 100% humidity. The prisms were then capped, as given in ASTM C 617 [14] (Fig. 2, Fig. 5), for flexural and compressive strength testing. After capping, the prisms were stored for 24 h at 100% humidity. After 48 h, the capped prisms were stored under water at 20 °C for five days. Seven days after the manufacture of the prisms, they were tested for flexural and compressive strength comparable to EN 196-1 [8]. Figure 2 shows the principle of the used flexural strength testing for 3D printed prisms. The forces measured in flexure were converted to strength values concerning the ideal cross-section of a prism (40 mm • 40 mm) and concerning the dimensions achieved by printing with the equation given in ASTM C293 [15].

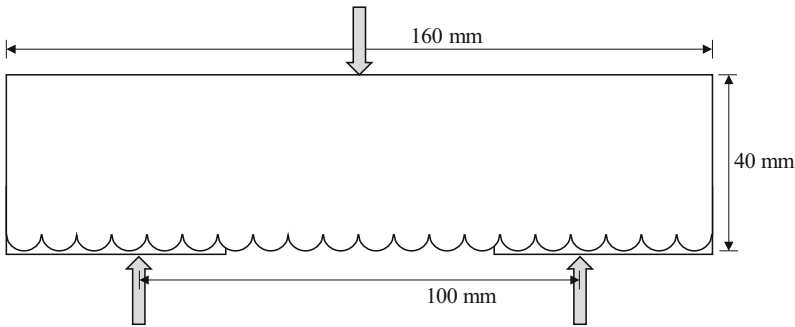


Fig. 2. Sketch of a capped 3D printed prism while test of flexural strength.

1.3 Molded Prisms

The molded prisms were manufactured based on EN 196-1 [8] with curing in water at 20 °C. To allow direct comparison with the printed prisms, the same materials as for the printed prisms were used. This resulted in deviations from the standard concerning the particle size distribution of the aggregates and the ratio of binder to aggregate.

1.4 Flow of Mortars

The flow of the mortars was determined according to EN 1015-3 [16]. The diameter was measured just after removing the conical mold before the 15 drops required for the standard procedure and then again after the material was dropped 15 times. Each result is the average of 4 measurements. The flow of each material was tested right after the preparation of the mortar. The flow was calculated as the average diameter increase of the sample and is expressed as a percentage of the original base diameter.

1.5 Ultrasonic Wave Transmission Velocity

To continuously follow the structural build-up of the materials right from the start of hydration, the materials were tested by measuring the ultrasonic transmission velocity of a 25 kHz ultrasonic P-wave during the first 24 h after water addition. For this

purpose, the device IP 8 by Ultratest was used. A measurement was conducted every 60 s. The mixing routine of the mortars was in accordance with EN 196-1 [8]. After mixing, the mortars were poured in the measurement cells and covered with a plastic foil. Testing took place in a laboratory room conditioned to 20 °C.

The longitudinal wave velocity of the ultrasonic wave strongly depends on the ratio of liquid to solid [17] and thus on the degree of hydration of a cementitious sample [18]. Reinhardt et al. [19] found that the initial setting of a mortar sample can be defined as the point of the first maximum in the curvature of the graphs in a velocity to mortar age plot. According to Reinhardt et al. [19], the mortar can no longer be mixed at this point. Further, Reinhardt et al. [19] suggested that the final set of a mortar sample, the point at which the mortar is no longer workable, correlates to the time at which the ultrasonic wave velocity reaches a value of 1500 m/s.

2 Results and Discussion

2.1 Flow Test

The results of the flow tests of the printing materials are given in Table 2. Figure 3 illustrates the influence of the 15 drops required by EN 1015-3 [16]. The diameter measurements right after the removal of the conical mold were performed on the bottom of each sample. These results indicate that each material was mainly able to support its own weight. The maximum spread of the material was determined with an increase of 19% concerning the diameter of the mold. Under the influence of the 15 drops, each material spread to a diameter of at least 13.8 cm. The highest spreads were determined for CEM-S and CEM+BS+LS with 49.1% and 48.7%, respectively. Especially the diameter after 15 drops varies considerably between the samples.

Table 2. Diameters and flow of 3D printing materials (average of 4 measurements).

Sample name	After cone removal [cm]	After 15 table drops [cm]	Flow [%]
CEM	10.2	13.7	34.3
CEM+BS+LS	11.9	17.7	48.7
CEM+LS	10.6	14.6	37.7
CEM-S	11.0	16.4	49.1

2.2 Comparison of 3D Printed and Molded Prisms

Figure 4 and Fig. 5 present images of the printed mortar prisms. The upper region of most prisms (Fig. 5a) showed some cavities lengthwise the prism following the ideal contact line of the filaments (“interfilament voids”) [5, 7]. Comparable voids parallel to the width of the prism were only rarely found. These voids occur as the four filaments which should join here do not touch in practice. As already mentioned, these voids mainly occur in the upper region of the prisms, which could be due to different reasons. On the one hand, the forces by the extrusion of the following layers and their weight

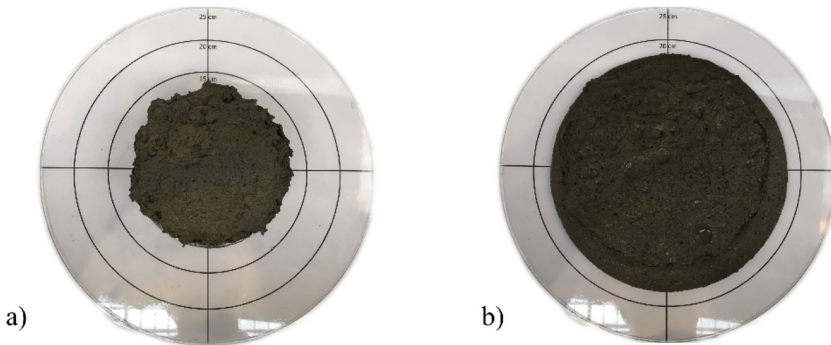


Fig. 3. Slump test of CEM+BS+LS. The diameter of the glass plate is 25 cm. The circles of the crosshair are at 5 cm off each other. a) Before the 15 drops. b) After the 15 required drops.

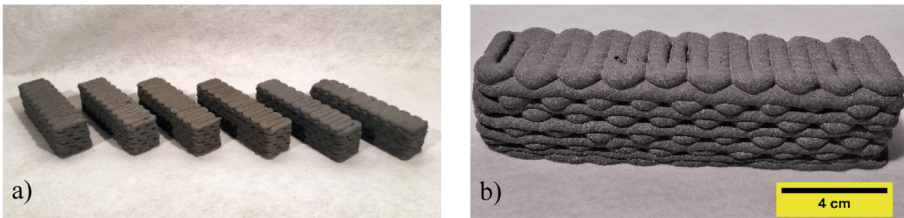


Fig. 4. 3D printed mortar prisms before testing. a) Prisms of CEM+BS+LS, CEM+LS, and CEM-S (from left to right, two each). b) Close up of 3D printed prism of material CEM.

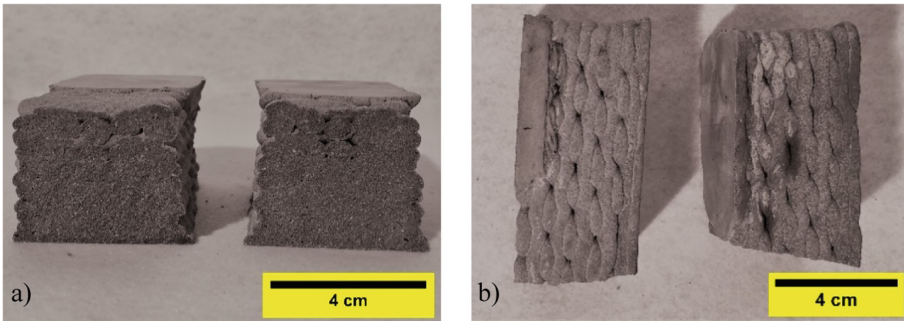


Fig. 5. 3D printed mortar prism of material CEM with capping after the flexural strength test. a) Frontal view. b) Side view.

could lead to a closure of the voids in lower layers. On the other hand, the material flow might have been selected slightly too small. This might lead to an increasing lack of material in the upper layers of any printed object.

For any layer below these top layers, the effects mentioned above do not occur. Here, the interconnectivity within a single layer and between the layers is very high and

the filaments cannot be distinguished in the cross-section (Fig. 5a). The crack, which occurred after the failure of the material in the flexural strength test (Fig. 5b), does not seem to follow the pattern introduced into the material by the printing process. Likewise, cracking between the horizontal layers of the prisms as reported by other authors [7] was not observed. Nevertheless, the crack originates in every case in the line between two filaments at the top surface of the prism.

The mean values of compressive strength (Fig. 6) of the 3D printed prisms are very close to those of the molded equivalents. This indicates that (sufficiently small) interfilament voids do not reduce the compressive strength of a material. Nevertheless, flexural strength (Fig. 7) was, especially if the deviations of the outer measurements are taken into account, considerably smaller. The main reason for this will be the slits on the upper surface of the sample introduced by the printing process which is the origin of the failure. Le et al. [7] found for specimens cut from 3D printed objects flexural strength values comparable high as for the molded equivalents which does not apply for the current specimen design. The standard deviations of strength values of the 3D printed prisms are considerably higher as that for the molded prisms in most cases.

When regarding the high flexural and compressive strength values achieved by the 3D printed prisms, it must be taken into account, that these prisms have been stored under water while curing, as required by EN 196-1 [8]. In large scale 3D printed structures, with surfaces subjected to contact with plain air, surface drying and shrinkage might occur, reducing the flexural and compressive strength of such components.

2.3 Comparison Between Materials

The materials developed in the current study have a lower w/b ratio than several published mixes [4, 9, 20, 21] which counteracts the problem of shrinkage [9]. Additionally, it was possible to develop 3D printable mixes with a low number of components. Hambach and Volkmer [6] and Zhang et al. [22] used comparable sand contents but also compositions with a sand to binder ratio of around 1.5 are already published [3, 23, 24]. A sand to binder ratio of 1.5 was also tried for the mixes here but the attempts were not successful due to frequent discontinuities of the extruded volume flow.

Figure 6 and Fig. 7 show that the strength values for the mixes CEM and CEM+BS+LS are comparable, whereas CEM-S shows slightly higher values, especially in flexural strength. The mixture CEM+LS shows considerably lower flexural and especially compressive strength. This is likely due to a lower share of reacting material in this mixture.

2.4 Ultrasonic Wave Transmission Velocity

Figure 8 presents the results of the ultrasonic P-wave velocity testing. All materials show an increase of ultrasonic wave velocity, presumably resulting from decreasing liquid to solid ratio by hydration, right after mixing. According to the definition by

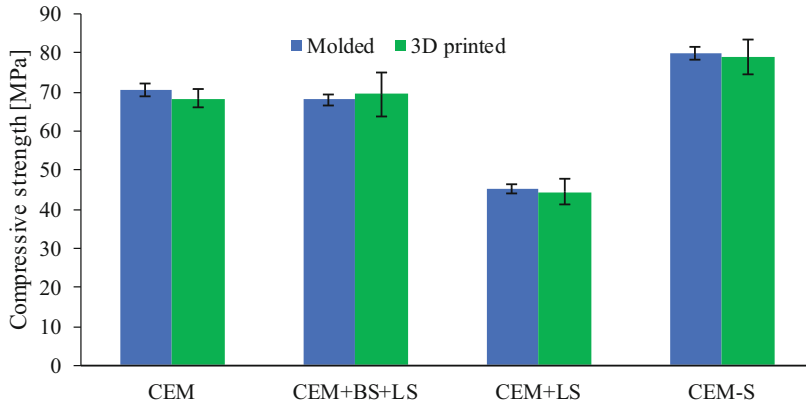


Fig. 6. Comparison of 7 d compressive strength of molded and 3D printed prisms.

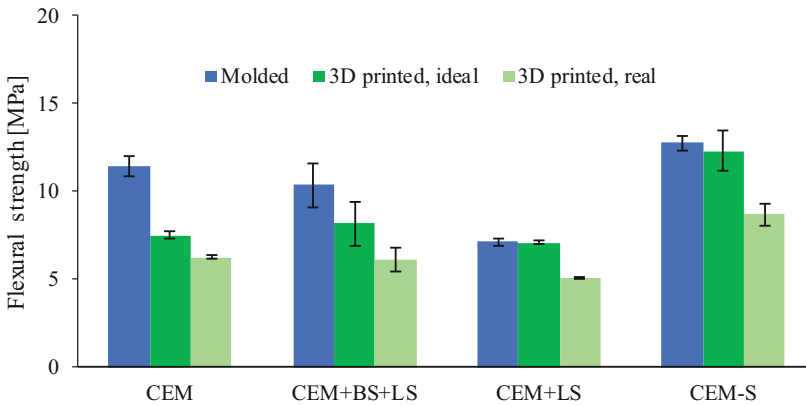


Fig. 7. Comparison of 7 d flexural strength of molded and 3D printed prisms.

Reinhardt et al. [19], every material reached initial set within 90 min after mixing. The final set was reached by CEM, CEM+BS+LS and CEM+LS just before 5 h after mixing. CEM-S reached the final set at 5.5 h. The retarded final set of CEM-S presumably originates from the reduced content of calcium sulfate in the binder. A reduced amount of sulfate carrier in cement paste can lead to an increased early reaction of the aluminate phases which in turn retards the silicate reaction. Different mechanisms were proposed for this delay of silicate reaction [25, 26].

After 24 h, all tested samples reached an ultrasonic wave velocity higher than 3000 m/s. The lowest wave velocity was reached by CEM+LS. A possible explanation is the amount of 50 wt% of ground limestone in the binder which is predominantly inert during cement hydration compared to GGBS or OPC itself.

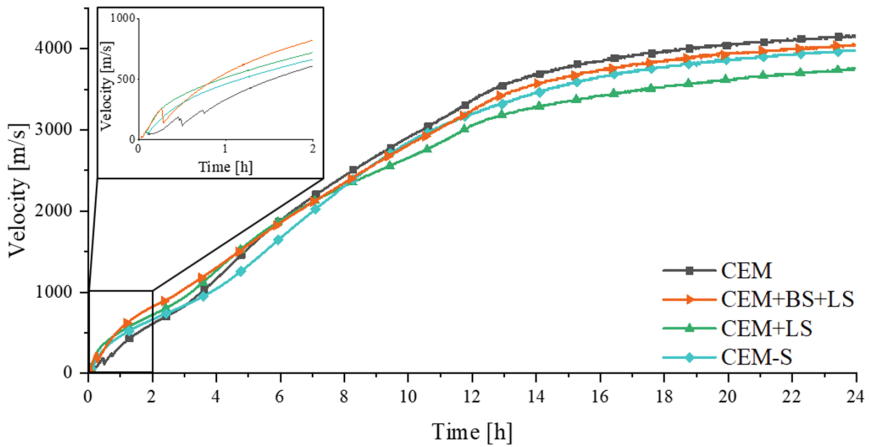


Fig. 8. Comparison of the ultrasonic P-wave velocity development over the first 24 h of hydration.

3 Conclusions

With the same curing conditions, the compressive strength of 3D printed prisms can be very close to molded prisms even if they exhibit internal and external imperfections typical for 3D printed objects. Nevertheless, these imperfections can have a significant impact on flexural strength. Four mortars with different binders printable on one 3D printer can vary considerably in their slump while meeting the requirements of pumpability, extrudability and printability. Binders based on OPC clinker mixed with a calcium sulfate addition which is lower as in standard OPC can be used in a 3D application and can perform equal to conventional binders. Nevertheless, care must be taken as a lower addition of calcium sulfate can lead to an undesired early and strong reaction of aluminates which in turn can delay the silicate reaction. An excessive delay in the silicate reaction must be avoided in order to prevent a decrease in strength.

Acknowledgements. The authors would like to acknowledge the funding of the German Federal Ministry of Education and Research of this work in the scope of the project BauProAddi [27] (FKZ: 03XP0122A). Special acknowledgement goes to Alexander Paatsch for fruitful discussions about testing of 3D printed samples. Moreover, we are thankful for the supply of basic materials by OPTERRA Zement GmbH and SIKA Deutschland GmbH. We owe Falk Martin, Isabelle Wichmann and Marcel Nasser for comprehensive help while performing the experiments and in sample preparation.

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Design of Energy-Efficient White Portland Cement Mortars for Digital Fabrication

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Abstract. Additive manufacturing, i.e. three-dimensional (3D) printing technology has many advantages over traditional processes and the related technology is continuously improving. This study aims to develop an energy-efficient White Portland cement (WPC) mortar mix suitable for 3D printing applications. The mortar mix contained a blended binder content using Çimsa Recipro50 calcium aluminate cement (CAC) along with Çimsa Super WPC (sWPC). Microencapsulated Phase Change Materials (mPCMs) added to the mix enhance thermal performance through latent heat storage capability. The CAC used in the study has an alumina content of at least 50%. Mineralogical analysis of the CAC and sWPC binder were characterized by the XRD-Rietveld method. In terms of material design for 3D printing, printable mortars must be workable enough to be extruded (extrudability) and retain its shape with little or no deformation after extrusion (buildability). In this study, the printability of mortar was evaluated through workability loss, open time, green strength, and early-age compressive strength. Results showed that use of sWPC and CAC composite enables a thixotropic behavior, which is required for 3D printing. The designed mortar mixes can enable high flowability necessary for successful extrusion and have high green strength at fresh state to maintain stable printing. The results also showed that the use of mPCMs can influence printability while improving buildability.

Keywords: Additive manufacturing · Calcium aluminate cements · White Portland Cement · Microencapsulated Phase Change Materials · Energy efficient mortar

1 Introduction

The emerging developments in Industry 4.0 revolution led the construction industry to rethink the material composition and production methodologies, particularly cement-based materials. These developments will enable design and production complex geometries without formwork and decreasing waste material generation and reducing the labor demand construction industry. However, increasing interest in digital production and additive manufacturing methodologies require advanced engineering of

cementitious materials, including material composition, reactivity, and printer properties. The printability of the material is related to extrudability, and buildability [1]. Extrudability is the ability of the material flow through the nozzle of a 3D printer, whereas buildability is the ability of the material to carry the subsequent layers without any deformation. Extrudability and buildability are competing properties such that extrudability can be obtained by high workability, while low workability is required for buildability [2]. These two parameters are related to each other by the yield stress. The yield stress of the concrete should be at a certain range to enable printing of certain layers [3, 4]. The initial yield stress value of the cement-based matrix right after mixing is related to layer height, the density of the mix and gravitational forces [5]. By the end of the printing process, the final yield stress of the lowest layer must be sufficient to carry the entire height which corresponds to a defined initial to final yield stress ratio [5]. Thus, the rheological requirements for cement-based mortars for 3D-printing are generally beyond the initial yield stress and viscosity, which mainly relies on the thixotropy of the material. While the material needs to be flowable enough to be extrudable and properly compacted, it also has to be stiff enough right after extrusion for stability. The stiffness upon printing, also referred to as buildability is related to the yield stress of the material and thixotropy which provides the shape stability of the layers.

Thus, the binder materials in the mortar design should enable the required thixotropy and early-age strength development. This alternately pushes the researchers to focus on alternative cementitious binders rather than Ordinary Portland Cement (OPC). One sound alternative for binding material can be WPC, which has been used in grouting and pre-cast concrete products, due to its high-early strength specifications. WPC can provide high early age strength development due to its fine particle size. In addition, CAC has been used to manipulate the rate of hardening in OPC blended cement [2]. WPC and CAC blends can increase the hardening rate to obtain favorable shape stability and buildability. However, it is required to evaluate the rheology and fresh-state properties of WPC-CAC blended mortars for additive manufacturing. In addition, studies revealed that mortar design for additive manufacturing requires high dosages of cementing materials at a lower binder to sand ratios, which reduces the economic and environmental impacts of 3D concrete printing technology.

Thermal energy storage (TES) is considered as one of the most important technologies for heating and cooling applications in buildings using renewables as a continuous source [6]. Integrating TES to printable mortars can enable a rapid construction without using any additional insulation membranes. In this case, incorporation of mPCMs in printable mortar matrix can be used to store large amounts of thermal energy as latent heat during phase transitions. This study focuses on evaluating fresh and hardened state performance of specially designed energy-efficient WPC-CAC mortar for additive manufacturing.

2 Materials and Methods

2.1 Material Selection

Çimsa Super White Portland Cement (sWPC) and Çimsa Recipro50 (CAC) were used to prepare mortar mixes for evaluating their printability. Table 1 and 2 summarize the oxide composition and phase distribution for these cements.

Table 1. Oxide composition for Çimsa Super White Portland Cement (sWPC) and Çimsa Recipro50 (CAC)

Super white cement	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	Na ₂ O	K ₂ O	MgO
(%)	69.89	18.57	3.52	0.22	2.95	0.13	0.43	0.63
Recipro50	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	Na ₂ O	K ₂ O	MgO
(%)	37.25	3.95	53.65	1.10	0.04	0.05	0.60	0.61

The mixes were prepared with silica sand having a fineness modulus of 2.88 with a maximum particle size of 1 mm. The water to binder (w/b) ratio was kept at 0.40. To improve the workability of the mix a naphthalene-sulphonate based high-range-water-reducer (HRWR) and a special powder additive (PA) were used. This polymer additive was specially designed for white cement-based mixes to improve flowability. The setting of the mortar was controlled by replacing a portion of the Recipro 50 CAC binder content by anhydrite gypsum. All mixes contain 12-mm polyvinyl alcohol (PVA) fiber and polymer additive (each by 0.5% of the total mortar mix volume). Fibers and polymer additive were included in all mixes due to their significant effects on properties of fresh and hardened state of printable mortars.

Mortar samples were prepared using standard sand according to EN 196-1 norm and the binder to sand ratio was 2. Table 3 summarizes the mixes and sample names used in this study. Both cement paste and mortar samples were prepared by ASTM C305-14 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars. To incorporate the liquid HRWR, two thirds of the mix water was added to the initial mix until the waiting period. Then, the superplasticizer was mixed with remaining water and added to the mortar mix during the last 60 s of the mixing. In samples with powder additives, all dry materials were added to the mixing bowl and homogenized for 30 s. Then, all the mixing water was added to the mix and mixing process was done according to ASTM 305-14.

2.2 Experimental Protocol

2.2.1 Evaluation of Workability with Time

In this work, the workability of the mixes was quantitatively assessed by a drop table flow test based on ASTM C230/230M-14 Standard Specification for Flow Table for Use in Tests of Hydraulic Cement. Then, the change in flowability for the mixes was measured over time after 0, 5 10, 30 and 40 min of mixing. The test was conducted on

Table 2. Phase distribution for Çimsa Super White Portland Cement (sWPC) and Çimsa Recipro50 (CAC)

Mineralogical phases (sWPC)	Super white cement (%)	Minerological phases (CAC)	Recipro50 (%)
C ₃ S – Alite	68.4	CA	77.7
C ₂ S – Belite	16.1	C ₁₂ A ₇	2.2
C ₃ A	4.8	C ₂ AS	11.5
Calcite	2.8	C ₄ AF	0.0
Periclase	0.1	C ₂ S- α	2.4
Quartz	0.3	C ₂ S- β	0.3

Table 3. Composition of mortar mixes prepared in the study.; RB: High range water reducer; PA: Powder additive

Sample name	sWPC (g)	Recipro 50 (g)	Gypsum (g)	w/c	Sand (g)	RB (g)	PA (g)	Polymer (g)	LiCO ₃ (g)
R50_5%_RB	427.5	22.5	–	0.40	562.5	7.5	–	9.2	0.09
R50_5%_PA	427.5	22.5	–	0.40	562.5	–	2.8	9.2	0.09
R50_20%_RB	368.1	36.8	45	0.40	562.5	7.5	–	9.2	0.09
R50_20%_PA	368.1	36.8	45	0.40	562.5	–	2.8	9.2	0.09
R50_10%_PA	368.1	36.8	45	0.36	562.5	–	2.8	9.2	0.09

triplicates of samples for each batch. Flow diameters were recorded as average values from these triplicates of samples.

2.2.2 Green Strength Test

The buildability of the 3D printing concrete materials was significantly related to its green strength. After mixing, the mortar samples were placed in 75 × 100 mm cylindrical molds. Then, the cylinder was removed after 30 min and a large tray or container was placed on top of the sample aligned to its center of gravity. The sand was gradually added to the container until the cylinder was obviously deformed or collapsed. The weight (including container) that caused the sample to fail was then converted to green strength.

2.2.3 Initial and Final Setting of Mixes

The workability of fresh concrete was also correlated to the initial and final setting times of the mortar mixes. Initial and final setting times were determined by ASTM C191-19 Vicat needle test. However, the test was modified, and a constant w/b was used instead of normal consistency. The initial setting time refers to the moment when the Vicat needle does not completely penetrate the test specimen (limited to 25 mm). Final setting time refers to when the Vicat needle no longer penetrates the specimens.

2.2.4 Compressive Strength

The compressive strength evaluation in hardened mortar samples was determined by EN 196-1 standard. Mortar mixes were poured into $40 \times 40 \times 160$ mm size beam molds and kept at 60% relative humidity (RH) at room temperature (20 ± 2 °C). All mixes contain 12-mm polyvinylalcohol (PVA) fiber and polymer additive as stated in Sect. 2.1. The samples were tested under flexural and compressive loading at 1, 3 and 7 days after mixing. The tests were done on triplicates of the sample.

2.2.5 Incorporation of mPCMs to Mortar

The mPCMs are produced by emulsion polymerization to produce PCM encapsulated in a polymer shell. The main parameters for mPCMs suitability for building applications are melting/freezing temperature and latent heat, size, and durability. Differential Scanning Calorimeter – DSC (Mettler Toledo DSC 3+) was used to determine melting/freezing characteristics in a temperature range of 0–50 °C at 10 °C/min scanning rate. Morphology analysis to determine the durability and size of mPCMs was done with Field Emission Scanning Electron Microscopy – FESEM (FEI Quanta 650). FESEM images of samples were taken after coating with Platinum. The composition of mPCM in concrete mixtures is recommended to be less than 5% to fulfill with mechanical strength according to standards [7]. In this study, mortars were prepared with 2% mPCM composition following this recommendation.

3 Results and Discussion

3.1 Workability Loss and Green Strength Development with Time

The flowability evolution is the simplest indicator of printability. This can be indication of workability loss, rate of hardening and buildability. The evaluation of buildability was also done with a drop table flow test (*see* Fig. 1). The flow table will target appropriate values for extrudability and shape stability under self-weight and buildability. As seen from Fig. 1, samples R50_5%_RB and R50_20%_RB showed a rapid loss in flowability. This was mainly attributed to the use of a HRWR, which was most commonly used in OPC, not WPC. Thus, the use of this HRWR decreased the workability of the mix, thus limiting their printability. In contrast, the use of powder additive (PA), which was specially produced for WPC, increased the workability of the mix. All samples containing PA showed high flowability right after mixing ($t = 0$). The results showed the decrease in flowability was mainly depended on Recipro 50 to gypsum ratio rather than the type of additive. In general, to obtain the optimum ettringite formation in the cement paste matrix the CAC to gypsum ratio should be adjusted. In the case of R50_5%_PA, there was not any gypsum incorporated and CAC ratio was also kept very low. Increasing CAC dosage and adding gypsum by 50% of CAC weight (R50_10%_PA) resulted with a high flowability but with a significant workability loss within the following 10 min of mixing. Depending on the printer, nozzle type and printing speed, this particular type of mix might be adequate for printing. In case of a slower extrusion process (<5 mm/s), this particular mix might result in clogging and cannot be printed. In this case a mix like R50_20%_PA might be

more suitable in terms of workability loss. This was adjusted by controlling the gypsum dosage, but this might interfere with the ettringite formation and cause cracking in the hardened state due to dimensional instability. Various combinations of common retarders like tartaric acid and citric acid to delay the initial setting are being tested for further optimization.

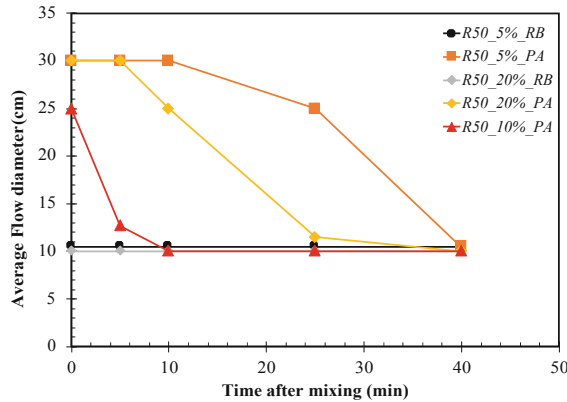


Fig. 1. Flowability evolution of sWPC - Recipro 50 Blended mortars with time. R50: Recipro 50; % value indicates % replacement of sWPC with Recipro 50 and Gypsum; RB: HRWR and PA: powder additive.

The early hardening tendency of sWPC-CAC blended mortars not only improves the buildability and shape-stability for the printed mortar mixtures but also decreases the open-time as well. As expected, fresh state green strength results were also in line with flowability evolution data (*see* Fig. 2). Further research is necessary to optimize the buildability with open time by using commonly used CAC retarders instead of adjusting gypsum content.

3.2 Setting Time and Compressive Strength of Mortar

CAC-Gypsum and CAC-OPC combinations are special types of binder systems, which are designed based on ettringite formation to achieve rapid strength development. In this study, different setting and hardening times were obtained through blending CAC with gypsum in a different ratio for an sWPC binder system. As stated in Sect. 3.1, the use of powder additive (PA) in R50_5%_PA mixtures of sWPC-CAC combinations increased the strength development rate but also increased both initial and final setting time. The presence of gypsum in R50_20%_PA and R50_20%_RB mixtures prepared as a ternary binder system (sWPC-CAC-CS*) significantly reduced the initial and final setting time. In addition, strength development in both mixes was decreased. It was observed that excess gypsum had a negative effect on the strength development of mixtures. The highest strength values were obtained for the R50_10%_PA mix with the least gypsum content. Based on the abovementioned results, rapid setting time and high

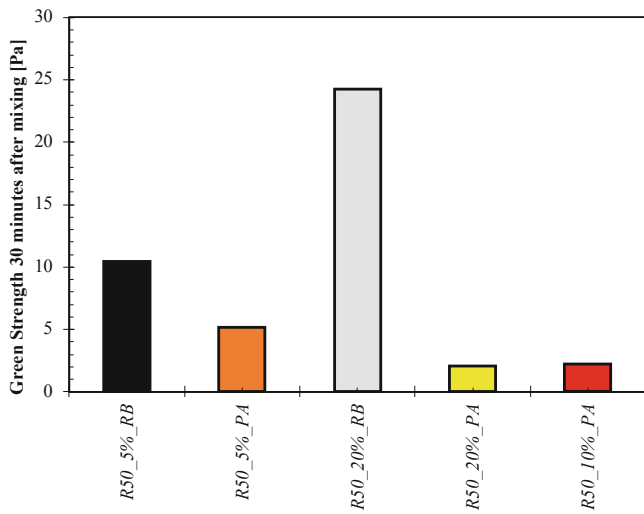


Fig. 2. Green strength of sWPC - Recipro 50 Blended mortars 30 min after mixing. R50: Recipro 50; % value indicates % replacement of sWPC with Recipro 50 and Gypsum; RB: HRWR and PA: Powder Additive. Bars represent the average green strength values for triplicates of samples.

Table 4. Compressive and flexural strength values for mortar samples

Sample name	Compressive strength (N/mm ²)			Flexural strength (N/mm ²)			Setting time (min.)
	1	3	7	1	3	7	
Age (day)	1	3	7	1	3	7	Initial:Final
R50_5%_RB	34.5	44.0	50.7	7.8	9.8	14.5	125:175
R50_5%_PA	38.9	53.5	59.3	9.5	13.4	13.5	155:360
R50_20%_RB	21.4	30.6	36.8	6.9	7.0	8.1	5:15
R50_20%_PA	25.0	36.8	43.1	8.1	8.8	9.1	55:200
R50_10%_PA	38.1	51.6	61.8	12.3	12.8	15.4	45:170

early strength can give an optimum ternary binder system, which is also beneficial in the digital production of cement-based materials (Table 4).

3.3 Influence of mPCMs on Printability and Hardened State of Mortar

Incorporation mPCMs in the sWPC-CAC mortar mixes have a significant potential to increase its thermal capacity [8]. The polymer shell of the mPCM should be durable to being mixed in the mortar and stay intact during phase change. This can be accomplished by designing robust microcapsules through adjusting size distribution and choosing shell material that can withstand thermal and mechanical effects. In our previous study [9], the size range of 250–850 μm and polymer shells prepared with

polymethacrylate and copolymers were found suitable for concrete mixes. The SEM image given in Fig. 3 for the mPCM used in this study shows that the microcapsules have uniform spherical shape with diameters in the range of 300–450 μm . The shells of mPCMs are unharmed and size is within robust range recommended by Beyhan et al. (2017). DSC results showed that melting temperature of mPCMs was 24 $^{\circ}\text{C}$ (peak temperature) and latent heat was 49.86 J/g. The melting temperature is suitable for thermal comfort in buildings, but the latent heat value needs to be improved. Further development on the polymerization process to improve microencapsulation ratio and latent heat is on-going.

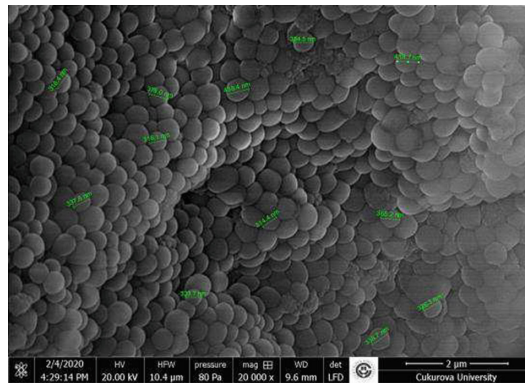


Fig. 3. SEM image of the mPCM

The results of mechanical strength and setting time for R50_5%_PA prepared with 2% mPCM are shown in Table 5. At the end of the first day, the flexural and compressive strength of R50_5%_PA_PCM2% formulation containing 2% mPCM was found to be 7.4 MPa and 25.8 MPa, respectively. Compared to R50_5%_PA, the reduction in flexural and compressive strength was 22.1% and 29.34% respectively. Similarly, 3-day and 7-day strengths of the mixture were decreased. These results show that 2% mPCM incorporation to the mortar mix can increase thermal storage capacity without affecting mechanical properties significantly. Further research has to be done to understand the potential heat capacity of the printed elements with the energy-efficient white cement mortar.

Table 5. Compressive and flexural strength values for mortar samples

Sample name	Compressive strength (N/mm ²)			Flexural strength (N/mm ²)			Initial and final setting time (min)
	1	3	7	1	3	7	
Age (day)	1	3	7	1	3	7	Initial:Final
R50_5%_PA	38.9	53.5	59.3	9.5	13.4	13.5	155:360
R50_5%_PA_PCM2%	25.8	39.9	41.9	7.4	10.4	12.4	110:345

4 Conclusion

This experimental study investigated the possible use of Çimsa Super White Portland Cement (sWPC) and Çimsa Recipro 50 Calcium Aluminate Cement (CAC) blends to develop printable mortar mix. Fresh and hardened properties of sWPC-CAC blends were investigated to understand printability. Different sWPC-CAC mixtures were developed based on the extrudability and buildability assessment of the mixes. The workability evolution and green strength test analysis showed that the printability of the mix can be controlled by adjusting the ratio of CAC and gypsum. In addition, these special cement blends provide various workability windows for printing applications. Yet, the results were promising in terms of developing buildability and extrudability at fresh state, further comprehensive analysis should be done to understand the thixotropy of the mixes. In addition, the compressive strength results revealed that excess gypsum had a negative effect on the strength development of mixtures. The highest strength values were obtained when there is a certain ratio in CAC and gypsum dosage was used. Further studies are being done to evaluate the performance of sWPC-CAC based mortars during printing process. The addition of 2% mPCM increased the thermal capacity of the mortar while changing mechanical properties but keeping the expected printability by improving buildability. Further studies are on improving heat storage capacity of mPCMs and determining their thermal effects on 3D printed elements are on-going.

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Use of the Chemical and Mineral Admixtures to Tailor the Rheology and the Green Strength of 3D Printing Cementitious Mixtures

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Abstract. Concrete 3D printing is an innovative manufacturing technic grasping a great interest in the construction industry. However, the materials engineering is still a challenge for an accurate large-scale 3D printing process. One promising solution is to tailor the rheological properties of the printing materials. Cementitious materials used for extrusion-based 3D printing should exhibit high static yield stress and well-adapted structuration (i.e. build-up) kinetics. These properties are mainly influenced by the mixture composition, including the use of the chemical and mineral admixtures. An experimental investigation was conducted to study the structuration kinetics of various mixtures by means of flowability and static yield stress evolution. Four mortar mixtures were developed using compatible chemical and mineral admixtures promoting the thixotropic behavior of printing materials. In addition, the green strength of mixtures was monitored up to 40 min after mixing. An empirical test setup and a novel sampling method were proposed to evaluate the behavior of the fresh 3D printed layers during the printing process.

Keywords: Cement-based mortars · 3D printing · Rheology · Static yield stress · Green strength

1 Introduction

Additive manufacturing or 3D printing is an emerging method of fabrication of concrete elements and is becoming widespread among industrial and academic sections. The extrusion-based 3D printing involves initially creating a 3D model compatible with the printer robot, and then printing the object through a mixing, pumping, and extrusion process. Faster and cheaper realization of complex geometries, high levels of the personalization, less need for manpower, and a better liaison with automated construction methods are the main advantageous of concrete 3D printing. However, there still exists several challenges toward industrialization of this method, one of which is the materials adaption to the 3D printing process [1].

Buildability is one important requirement of the printing materials. This is due to the absence of the conventional formworks which sustain the weight of materials before setting. In addition to their own weight, in concrete 3D printing, the deposited

layers should resist the increasing weight of upper layers without noticeable deformation. Thus, it is critical to obtain an accurate and qualitative understanding of the static yield stress and stress-deformation behavior of the cement-based printing materials. The behavior of such materials after yielding is more similar to elasto-plastic solids than viscous fluids. Therefore, adapting the stress-deformation approaches may allow a better characterization of the printable materials than the rheological models. This method has been referred to as the green strength of fresh mixtures and was proved to provide reliable results. Perrot et al. [2] used a compressive strength loading cell to apply an incremental normal force to the fresh cement pastes. The force was increased until the failure of samples. The authors reported good correlations between the yield stress and the green strength measurements. In addition, Kazemian et al. [3] adapted a custom-made vertical loading setup which was used as a criterion to ensure the buildability of the printing materials.

In this study, an experimental investigation was carried out to evaluate the static yield stress and the green strength of zero-slump thixotropic cement-based materials. Based on the preliminary results, four different mortar mixtures with similar initial flowability were optimized. The investigated mortar mixtures were subjected to different test methods, including the mortar flow, static yield stress, and the green strength.

2 Experimental Program

2.1 Materials

A general use (GU) Portland cement was employed as the main binder to produce the mixtures. Also, a ternary binder (TerC³) consisting of 75% GU, 20% class F fly ash, and 5% silica fume was used as the binder for one mixture. A pre-dispersed attapulgite nanoclay slurry with magnesium alumino-silicate needle-shape particles was used [4]. The attapulgite nanoclay had an average length of 1.75 μm and an average diameter of 30 nm. Chemical admixtures included a polycarboxylate ether (PCE) based high-range water-reducer (HRWR), and a modified starch as viscosity-modifying agent (VMA). A well graded quartz sand with maximum aggregate size of 1.25 mm and a specific gravity of 2.66 was used to proportion the investigated fine mortar mixtures.

2.2 Mortar Mixtures Proportioning

The mix design of the mortar mixtures is summarized in Table 1. The investigated mixtures were proportioned with a water-to-binder (W/B) and a sand-to-binder (S/B) ratios of 0.32 and 1.0, respectively. The dosages of chemical admixtures were adjusted to achieve a target initial flow of 152.5 ± 2.5 mm.

Table 1. Proportioning of the investigated mortar mixtures (W/B = 0.32 and S/B = 1.0)

Mixture ID	Binder type	Dosages of the chemical and mineral admixtures
M1	GU	–
M2		Nanoclay = 0.5% wt. binder, PCE = 0.36% wt. binder
M3		VMA = 1% wt. binder, PCE = 0.28% wt. binder
M4	TerC ³	Fly ash class F = 20% wt. binder, silica fume = 5% wt. binder, PCE = 0.18% wt. binder

3 Testing Methods

Three testing methods, including flowability of mortar, static yield stress, and green strength were employed. Flowability of the mixtures was evaluated using the flow table in accordance with ASTM C1437 specifications. This test was found to be suitable for printable materials based on previous works of the authors and the literature [5] to ensure an extrudable yet stable shapes of printed material. On the other hand, static yield stress of the investigated mixtures was measured using the coaxial cylinders ConTec 6 rheometer. The samples were initially pre-sheared with a rotational velocity of 0.5 rps for 10 s. In order to measure the static yield stress the constant shear rate method was employed using a constant rotational velocity of 0.005 rps. It is worthy to mention that due to rapid rigidification of the investigated mixtures, the rheometric measurements were feasible up to 20 min, while the other tests were carried out up to 40 min after the first contact between the binder and water.

In order to evaluate the resistance of the printed layers under gravitational loads of the upper layers (green strength), an empirical testing method was proposed. As shown in Fig. 1a, the proposed setup consisted of vertical and horizontal supports, a reservoir containing 200 ± 20 g steel beads equipped with a measuring needle, a ruler, a balance, and a timer. An undisturbed sampling method which involved taking 4 samples immediately after the mixing procedure was used. Accordingly, the mortar was placed inside an outer 100-mm diameter cylindrical mold to a fixed height of 60 mm. The inner cylindrical mold having 60 mm diameter and 60 mm height was then inserted into the mixture to sample the testing specimens (Fig. 1b). The samples were kept under controlled humidity and temperature until the testing time. At the time of testing, both cylindrical molds were removed, and the sample was subjected to a uniformly distributed normal force (Fig. 1c). The samples were vertically loaded by gradually adding steel beads at a constant loading rate of 40 g/s (0.39 N/s). The deformation of the sample was recorded as a function of the normal force using a fixed ruler attached to the testing setup and a needle attached to loading plate. The data recording was stopped at strain value of 40% for all the samples (Fig. 1d). The total strain was calculated using the ratio of the deformation to the initial height of the samples (60 mm).

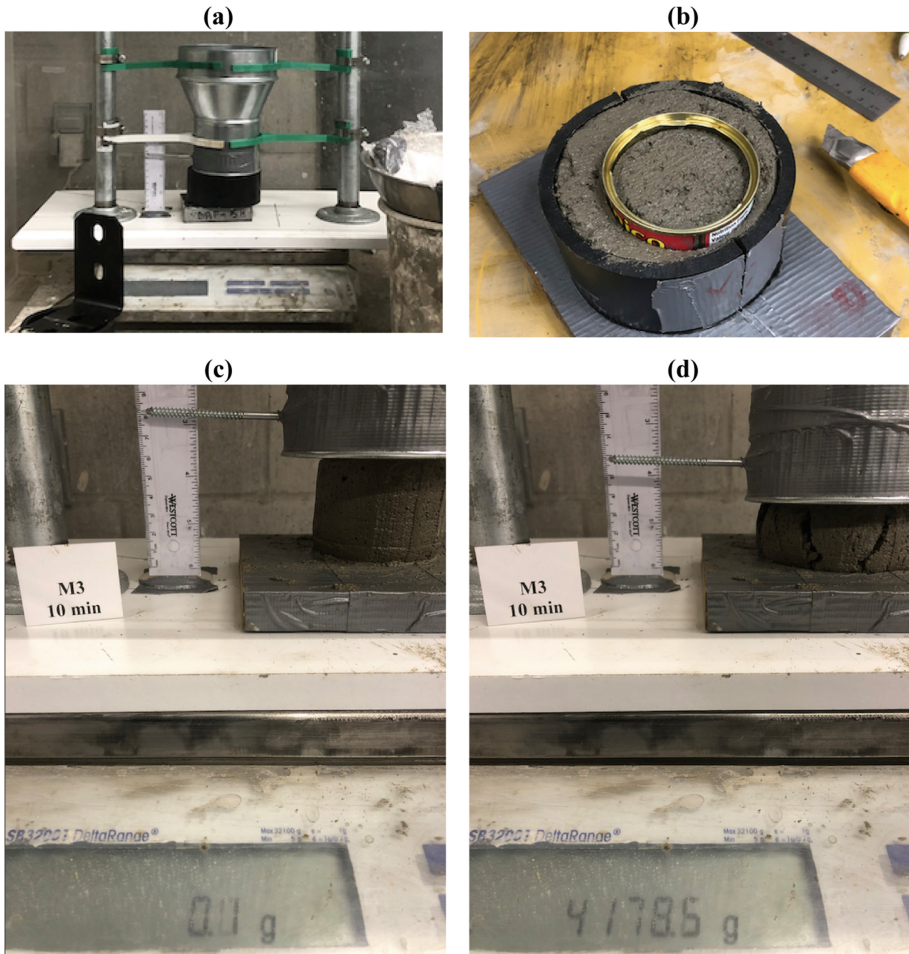


Fig. 1. (a) Green strength setup, (b) the proposed sampling method, the sample between the loading plates, (c) before any loading and (d) after failure.

4 Results and Discussion

4.1 Flowability

The target initial spread (measured 10 min of age) ranged between 150 to 155 mm. This range represents the flowability of mixtures with proper extrudability and self-weight shape stability based on the previous works of the authors. The spread of the investigated mixtures before applying any drops ranged between 100 and 102 mm, which indicated of the stability of materials against their own weight.

The PCE dosages were accordingly adjusted (Table 1) to achieve the targeted flowability of the investigated mixtures. The use of the optimized PCE dosage resulted in mortar mixtures with similar initial flowability to that of the control mixtures (M1).

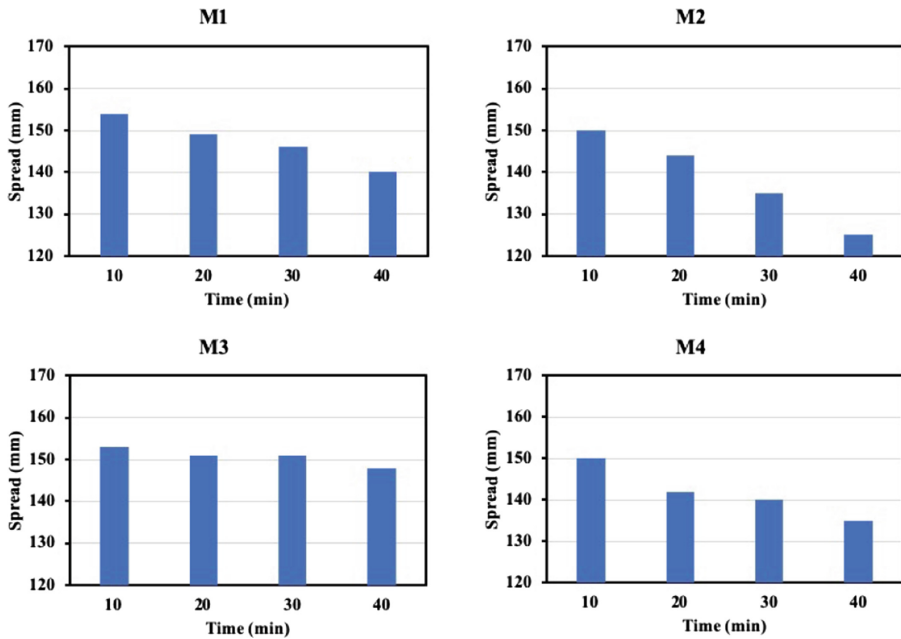


Fig. 2. The flowability variation of the investigated mixtures up to 40 min of age.

The flowability loss of the investigated mortar mixtures up to 40 min after the first contact between the binder and water is shown in Fig. 2. As can be observed, the flowability values determined at an age of 10 min are within the pre-selected range of 150 to 155 mm. On the other hand, the incorporation of different admixtures led to different trends in terms of flowability loss with time.

The combination of attapulgite nanoclay and PCE (M2) resulted in an acceptable initial flowability of 150 mm, but a significant flowability loss overtime. This can be due to the promotion of flocculation induced by the nanoclay particles, which then resulted in higher rate of rigidification overtime. The addition of VMA (M3) contributed into a pronounced thixotropic behavior considering the behavior of the samples before (at rest) and after the drops of the flow table (after shearing). VMAs are reported to have a bridging effect due to their absorption on the surface of the cement particles. However, depending on the molecular mass of the VMAs the bridging effect could be vanished provided that enough energy is used to disturb the mixtures [6]. The instant formation and the breakage of the bridges at rest and under shear, respectively, could be considered as a thixotropic behavior in mixtures containing VMA. The mixture M3 exhibited the lowest flow loss in time after being subjected to the flow table drops. This might be due to sensibility of this mixture to shearing (here table drops) which is referred to as de-structuration [4]. Accordingly, the spread loss values of 20 mm were obtained for M1 and M4, while M3 exhibited a low value of 5 mm over 40 min after the mixing.

4.2 Evolution of the Static Yield Stress

The static yield stress values of the investigated mortar mixtures are shown in Fig. 3. As compared to the control mixture (M1), the nanoclay mixture (M2) had the highest static yield stress values which, as mentioned earlier, can be due to the higher re-building kinetics induced by nanoclay particles [6]. In the case of VMA mixture (M3), a lower increase of the yield stress was observed from 10 to 20 min of age. This was in agreement with the flow table test results where M3 showed the lowest spread loss during the time. Despite the fact that during the static yield stress measurement, the material is subjected to a very low shear rate, hence the shearing effect during the test is negligible, the process of sampling disturbs the materials. Disturbing the material during the sampling (i.e. shearing) affects the rheology of the materials with high thixotropic properties and consequently results in lower changes of yield stress over-time. Furthermore, the M4 exhibited a moderate increase of yield stress similar to that of the control mixture. The addition of PCE in combination with fly ash is reported to decrease the yield stress, however, the presence of silica fume led to higher static yield stress values of M4 as compared to M1. This is due to the promotion of C-S-H gel formation and, consequently, a denser network resulting in higher static yield stress values [7].

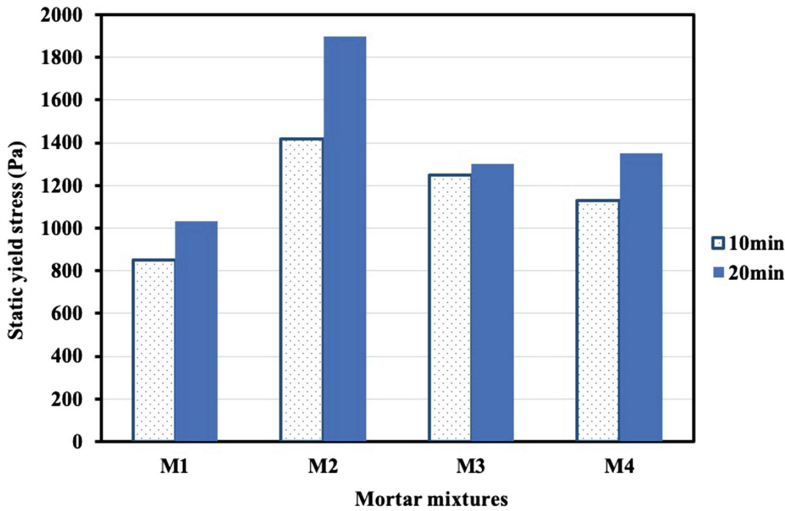


Fig. 3. Variation of static yield stress of the investigated mortar mixtures at 10 and 20 min of age.

It is worthy to mention that in the case of 3D printed materials, rotational rheometric methods can bring several challenges when measuring the static yield stress. Accordingly, performing this test using ConTec 6 rheometer was found to be not feasible at 30 and 40 min after mixing due to (1) rheometer limited torque (2.5 N.m), (2) difficulties with sampling due to highly rigid mixtures, (3) non-reversible traces of

the rheometer cylinder blades within the rigid samples. Thus, an alternative approach is proposed to evaluate the green strength properties of printable cement-based materials which will be elaborated upon the following section.

4.3 Evolution of the Green Strength

The force-strain relationships, measured at different ages (10–40 min), and the photos of the fractured samples, indicating typical failure modes of the investigated mortar mixtures, are presented in Fig. 4. A final strain value of 40% was selected for the data representation aiming to achieve consistency in the results. However, the tests were continued until the final failure of the mortars and the pictures on the graphs show the final condition of the samples. As shown in Fig. 4, for a given applied normal force, the M2 and M3 mixtures exhibited the lowest strain values, corresponding to the highest deformation resistance. This is in agreement with the static yield stress values that revealed the considerable effect of nanoclay and VMA on the rigidification of the mixtures at rest. Nanoclay was reported to give a rapid stiffening property to cement paste due to the rapid flocculation of the cement particles [6]. This can be more obviously observed in the green strength test performed on non-disturbed samples, such as those investigated in this study. In the case of M3 mixture, the combined addition of PCE and VMA led to more plastic deformation comparing to M2, which contains nanoclay and PCE. It is worthy to mention that despite its capacity in bearing high normal force (up to 160 N), M2 samples failed at relatively low strain values (up to 7%) showing large shear cracks (Fig. 4). Considering the requirements of 3D printing namely, extrudability and shape stability, M3 and M4 mixtures showed better performance due to their higher plastic deformability and lower risk of elastic buckling.

For all the investigated mixtures, the force-strain behavior can be divided into 3 zones, including the strain values less than 5%, between 5% and 30%, and higher than 30% (as indicated by the dashed lines in Fig. 4). Considering the average force-to-strain ratios (i.e., average slope of the graphs presented in Fig. 4), it can be observed that in the second zone (5–30% strain), all the mixtures showed a higher linear increase of strain with the incremental charge compared to those of the first zone (<5% strain). This can be explained by a transition between quasi-elastic and quasi-plastic phases of the investigated mixtures. The formed network in cement paste matrix along with the rigidification mechanisms due to the formation of the flocs lead to the initial resistance to a specific value of deformation, corresponding to 5% strain. However, beyond this specific deformation, the coupled effect of rigid network and flocs diminishes, and the higher rate increase in strain can be observed in the second zone (5–30% strain). Furthermore, a closer observation of the force-strain responses of M1, M3, and M4 reveals that after reaching around 30% strain, the slope slightly increases. This corresponds to higher resistance for a given deformation between 30 and 40% in zone 3. This can be due to the fact that, in the present study, a constant mass method was used for green strength measurement [8]. Indeed, a given mass of the sample is vertically deformed due to the applied normal force and, consequently, the loaded area increases. Moreover, for a strain of 30%, the samples have additional age of 2 min from the beginning of the test. These can, therefore, led to possible more resistance to the increasing load.

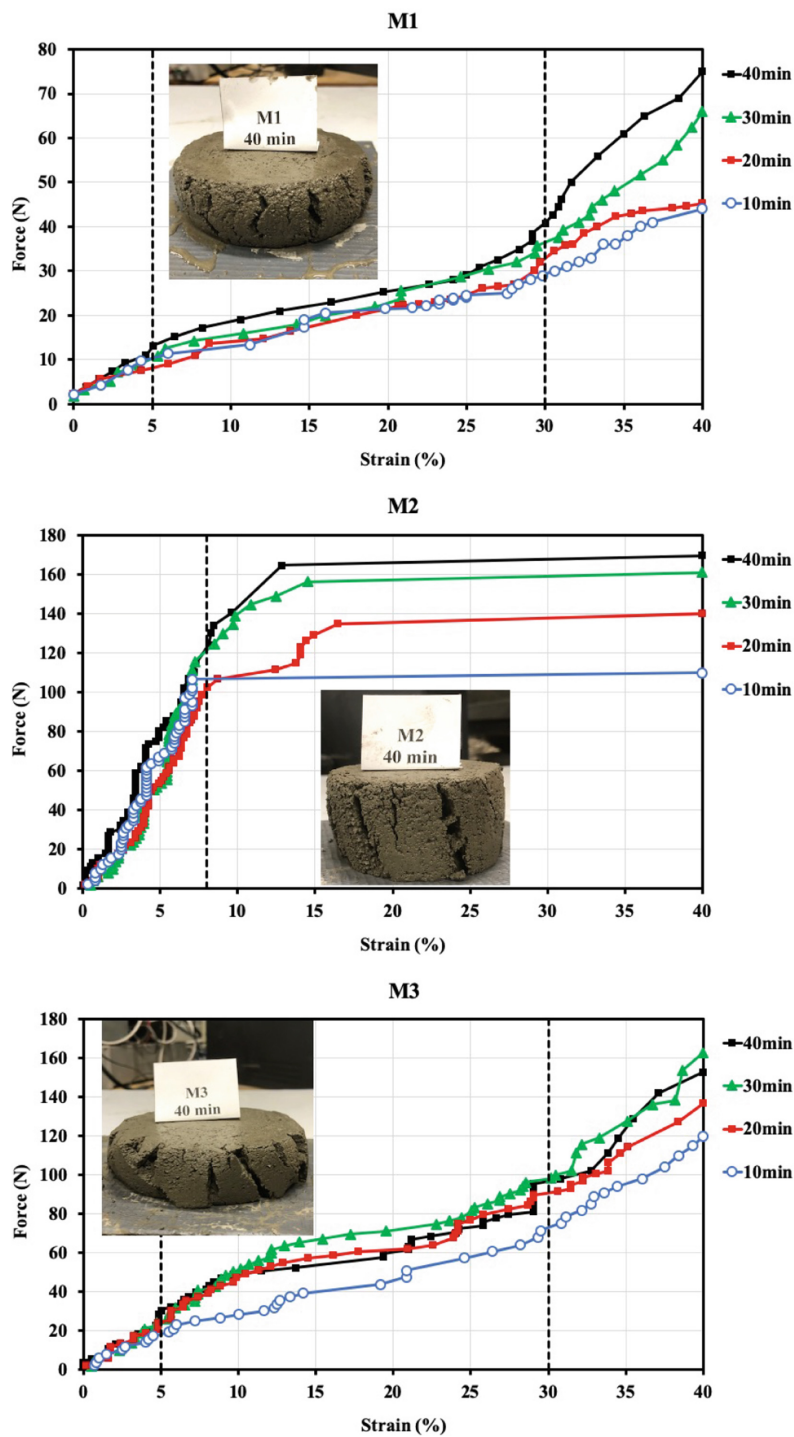


Fig. 4. Force vs strain behavior of M1, M2, M3, and M4 mixtures.

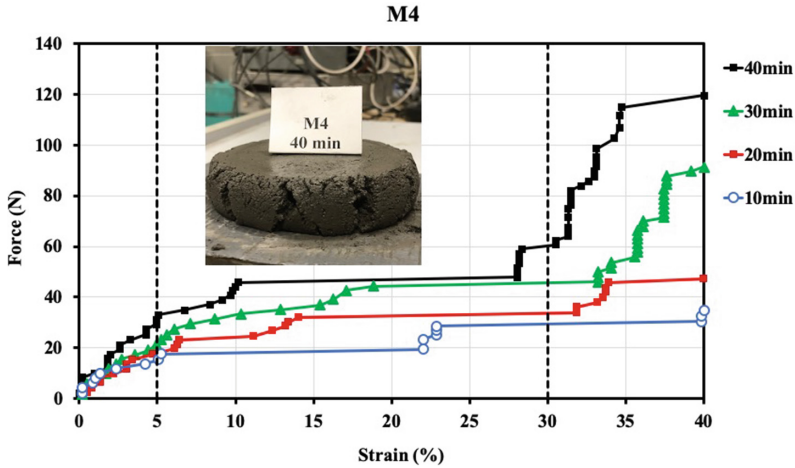


Fig. 4. (continued)

As can be observed in Fig. 4, the tested samples showed a higher resistance against the normal force at various periods of time. However, this effect is less pronounced in the lower strain zone (i.e. zone 1). For instance, M1 and M3 mixtures showed a relatively more sustained force-strain behavior (until 40% strain) and less time-dependent evolutions comparing to those of M2 and M4 mixtures for the whole testing time. In addition, a stepwise force-strain increase can be observed in the case of M4, regardless of the testing age. The stepwise behavior was found to be a result of multiple sudden increases in strain visually observed by formation of the cracks. However, as opposed to M2 the sudden formation of cracks in M3 did not result in a brittle failure of the sample, but instead, was followed by further resistance against the increasing force. This can be due to the coupled effect of loading inertia and presence of the fly ash. Indeed, the incorporation of the spherical particles of fly ash resulted in bearing effect, hence reducing the interparticle frictions in the mixture and, therefore, promoting sliding phenomenon between the particles.

5 Conclusions

The effect of chemical and mineral admixtures on the rheological properties of thixotropic cement-based mortar mixtures for 3D printing was investigated. Conventional methods to evaluate the build-up of the mortars, such as flowability loss and the evolution of the static yield stress were employed along with a proposed empirical green strength test method. According to the presented experimental results in this study, the following conclusions can be pointed out:

- The incorporation of thixotropy-enhancing admixtures, such as nanoclay and viscosity modifying agents, led to a higher demand of superplasticizer to achieve the targeted initial flowability, i.e. extrudability.

- The conventional flowability tests was useful to understand the structuration kinetics of the mixtures, but they found to be misleading depending on the shear thinning response of the mixture. Thus, undisturbed sampling methods are critical to test the materials with high thixotropic behavior.
- The static yield stress measurement can be criticized in the case of cement-based materials used for 3D printing due to their rigidity. This method poses difficulties for proper sampling and adequate testing procedures using normal rheometers.
- The green strength measurements using the proposed test setup was found to be a suitable method to study the behavior of the printing material in its fresh state. By analyzing the force-strain responses of the investigated mortar mixtures, three different strain zones were observed. The aforementioned zones provided information on the transition between quasi-elastic and quasi-plastic behaviors, and also the effect of the applied constant mass during testing procedure.
- The use of nanoclay and VMA considerably increased the green strength of the investigated mixtures due to the promotion of flocculation. However, the use of nanoclay resulted in a brittle failure mode, while VMA inclusion resulted in a more pronounced plastic deformation. On the other hand, the incorporation of fly ash led to bearing effect i.e. sudden strain increases.

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Characterising Concrete Mixes for 3D Printing

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Abstract. The construction industry is currently experiencing significant change as building information modeling (BIM), digital design and construction automation are exerting intense pressure on traditional technologies. As an advanced manufacturing technology, three-dimensional (3D) printing has significant potential applications in the construction sector, by utilizing a programmable robotic arm with a nozzle jet, 3D printing can enable us to construct complex concrete structures layer by layer. This new construction technique offers an advanced approach that can potentially accelerate the construction time and improve efficiency. They can work 24/7, even in a hazardous environment while minimising human errors. However, as an advanced cutting-edge technology, there are several remaining challenges to be overcome in comparison to traditional concrete casting, and these include appropriate pumpability, extrudability, buildability, compressive strength and open time for printing concrete. To overcome these challenges this project will investigate the effect of nanoclay to improve the fresh properties of printing concrete. It is considered that by utilizing different amounts of nanoclay and superplasticiser in the mix it will be possible to significantly affect the fresh properties of 3D printed concrete.

Printable materials, like any other cementitious materials, flow only when submitted to stresses higher than a critical yield stress. In this project, a shear vane test was used to measure the yield stress of cement-based materials in the lab.

Keywords: Vane shear test · Concrete 3D printer · Rheology · Nanoclay

1 Introduction

In the last few years, three-dimensional (3D) concrete printing has drawn significant attention due to its potential to modify traditional building practices. As an advanced manufacturing technology, concrete 3D printing can revolutionize the supply chain in the construction process by automatically producing building elements with complex geometries layer by layer, directly from a predefined digital model [1]. This new construction technique offers an advanced approach that can potentially accelerate construction time, make more efficient use of materials and reduce construction costs. They can work 24/7, even in a hazardous environment while minimising human errors and without formwork.

Despite these advantages, there are a number of challenges compared to traditional cast concrete and these include pumpability, extrudability, buildability, compressive strength and open time. Research has shown that the most critical properties in the fresh

state of concrete printing are extrudability and buildability. For successful concrete extrusion, the material should have sufficient flow and workability to provide a continuous easy-flowing paste from the source to the printing nozzle. Once the material is extruded, the printed layers must have sufficient shear strength to withstand its own weight and the weight of the following layers printed above it [2]. In other words, the concrete must have a low viscosity and stay fluid while inside the pump and nozzle, and should then have enough buildability characteristics to lay down correctly, remain in its position, and be solid enough to support the above layers without deformation or collapsing and provide a good bond between layers [3]. In concrete 3D printing, unlike metal and plastic printing, the material should not harden instantaneously so as to avoid cold joints between the layers [4]. In concrete, the pump should apply sufficient force to exceed the yield stress of the material, causing it to flow and extrude through the nozzle. Once extruded, the high yield stress enables the material to prevent deformation and resist flow in the material. In addition, the yield stress of the extruded concrete grows with time due to the reversible physical changes in the structure due to thixotropy and irreversible chemical and structural changes due to the hydration of cement over time [2]. As the increase in yield stress allows more layers to be deposited over time, this is considered as one of the key parameters for admixtures design. An optimum range of yield stress is desirable, as a high yield stress is required to prevent deformation of the extruded layers; however if the yield stress is too high the plastic viscosity can exceed the capacity of the pump and lead to extrusion problems [2]. As previous research has shown, a thixotropic material is the most appropriate for this purpose as it can be extruded smoothly and has the ability to hold the weight of the above layers by providing shape stability [5–7]. In this context the introduction of a thixotropic material such as nanoclay could be an effective additive for printed concrete.

Recent advances have made it easier for scientists to study nanoscale admixtures and their effect on the structure of concrete. Nanomaterials are very reactive because of their small particle size and large surface area and have great potential in improving concrete and cement properties (e.g. compressive strength and permeability). nanomaterials act as a nano reinforcement that strengthen the interfacial transition zone between the aggregate and the cement paste to improve the hydration of cement phases and enhance the strength of the cement matrix [20]. The potential benefits of using nanomaterials are their high reactivity, the need for smaller amounts and cost-effectiveness. Since nanoclay is finer than cement particles it can fill the micro and nano pores created by the relatively large cement particles and increase the shear and compressive strength [8]. Nanoclay improves the compressive strength by two mechanism. Nanoclay activate and promote the pozzolanic reaction with CH liberated during cement hydration to form further C-S-H, C-A-H and C-A-S-H hydrated products. These products close and compact the available open pores and create nanostructure [9]. Nanoclay also improves the interfacial transition zone by acting as a filler and packing factor into interstitial space [10]. Nanoclay particles can retain water due to their high surface to volume ratio which can improve hydration of cement [11]. The application of nanoclay in the mix has been shown to improve the shape stability for extruded elements [2, 12]. In a study by Morsy et al. [13], it was declared that incorporation of up to 6 wt.% nanoclay increases the compressive strength of blended

mortar by 18% when compared to plain mortar. Scanning electron microscopy (SEM) tests can also indicate the density and bond strength of the microstructure of the nanoclay admixtures. Nanoclay can accelerate the setting time of cement at room temperature. The presence of nanoclay can also reduce the time required for the calcium silicate reaction with water to produce calcium-silicate hydrate (C-S-H) and Portlandite. Research has shown that it can be reduced from 5 h for mixes without nanoclay to less than 30 min in the case of 4 wt.% nanoclay [14]. Kawashima et al. [15] stated that addition of nanoclay to fresh mortar increases the apparent viscosity due to increased flocculation, and this phenomena could be more effective in the presence of extra free water to enable dispersion of nanoclay in the mixture, and was associated with an increase in the yield stress.

While few past studies have provided an initial understanding of adding nanoclay to the concrete 3D printing admixtures design, extensive research and experimental data on the characterization of fresh state behaviour of printing concrete requires further investigation.

Furthermore, Portland cement concrete has been found to be the most widely used and viable choice of material as 3D printed concrete develops in the near future. The main reasons are the well understood properties of fresh and hardened concrete and a wide range of readily available admixtures to customize its performance [12].

The aim of this study is to investigate and evaluate the effects of nanoclay and superplasticiser on the fresh properties of a printing admixture. This paper presents a yield stress based admixtures design approach for Portland cement concrete. The structural build-up with time is evaluated by performing yield stress measurements after different rest durations and utilises a shear vane for direct measurement of the yield stress.

2 Materials and Methodology

2.1 Materials and Mixtures Design

Based on previous research [12], printing concrete can be characterized by high powder content, no coarse aggregate and the use of viscosity modifying admixtures (VMA). In this study, Portland cement Type II was used to produce printing concrete. Sand with a maximum aggregate size of 2 mm was used as a fine aggregate and the aggregate grading is presented in Table 1. Sika® ViscoCrete, a polycarboxylate (PCE) based superplasticizer, was added to the admixtures to increase the flowability of concrete, reduce the water to binder ratio and improve self-compaction properties. The recommended dosage of ViscoCrete according to manufacturer's ranges from 0.2% to 2% by mass of cement. The selected amount of superplasticizer for this study was 0.2% and 0.4% by the mass of cement. In addition, Sika® stabilizer- 4R a VMA was added to all mixtures at 0.1 wt.% of cement content to increase the plastic viscosity and yield stress of the printing concrete.

The nanoclay used was a thermal treated, highly purified attapulgite clay supplied by Actigel®, and was applied to improve the thixotropic characteristics. When nanoclay was dispersed in water, it was needle shaped with an average particle length of

1.75 μm and average particle diameter of 3 nm. The specific gravity of this nanoclay is 2.29 and the aspect ratio of 583 is very high. Hence, it may form a highly entangled gel even at small solid concentrations, provided they are appropriately dispersed into individual particles [16]. The high aspect ratio of nanoclay has been mentioned in previous research works [4, 12, 16] and the manufacturer’s data sheet.

Table 1. Sieve analysis of fine aggregate.

Sieve size (mm)	Percent passing (wt.%)
2	100
1	77
0.5	44
0.25	17.25
0.063	2

All paste admixtures have a water to cement ratio of 0.43 by mass. The designed water was divided into two parts. 95% of water was mixed with cement in the beginning, the remaining 5% was mixed with nanoclay. The nanoclay powder was blended with the mixing water in a Waring blender at a speed of 12000 rpm for 2 min to produce a clay suspension and remains stable after 24 h at rest as was suggested by Qian and De Schutter [17]. The amount of nanoclay addition varies from 0, 0.25 and 0.5% by mass of cement. All mixes were prepared using a bench top mixer and mixed for 12 min. Water was initially mixed with cement and sand for 2 min, at which point the superplasticizer, VMA and nanoclay were added to the mix (Table 2).

Table 2. Proportions of admixtures.

Mixture	CEM II (gr)	Water (gr)	Sand (gr)	Nanoclay wt.%	Superplasticiser wt.%	VMA wt.%
1	600	259	1379	0	0.2	0.1
2	600	259	1379	0.25	0.2	0.1
3	600	259	1379	0.5	0.2	0.1
4	600	259	1379	0	0.4	0.1
5	600	259	1379	0.25	0.4	0.1
6	600	259	1379	0.5	0.4	0.1

Six mixes were designed and the extrudability and buildability of the admixtures was evaluated in terms of a change in yield stress with small changes in the superplasticizer and nanoclay dosage.

2.2 Shear Vane Test

A shear vane apparatus was applied to investigate the workability of printing concrete. This approach was chosen as it derives a relevant, scientific rheological parameter and can also evaluate the workability at different times in the production process.

After mixing, the concrete was transferred to a cylinder container and a soil shear vane apparatus was used to measure the yield stress of the mixtures. A four-blade vane (12.7 mm × 12.7 mm) was used. The depth and diameter of the container (42 mm × 42 mm) was at least twice as large as the length and diameter of the vane to minimize any rigid boundaries effects [18]. The mixtures were subjected to a constant rotation of 0.1 rpm and the maximum torque value was recorded and converted to yield stress using Eq. (1) [2]:

$$T = \frac{\pi}{2} D^3 \tau_y \left(\frac{H}{D} + \frac{1}{3} \right) \quad (1)$$

Where T is the maximum torque, τ_y is the yield stress, H and D are the height and diameter of the vane. The workability of the new fresh sample of concrete was measured every 10 min using the shear vane to determine the open time.

2.3 Compressive and Flexural Strength

The concrete mix design should meet performance requirements in the fresh and hardened state. The main properties of the hardened concrete are the flexural and compressive strength. These properties were assessed at 7 days by testing prepared prism samples (160 × 40 × 40 mm³) according to EN 12390-3 [19]. Three samples were tested for each set and their average value was reported for each admixture.

2.4 Slump Flow Test

The slump-flow of each mixture was also tested using a flow table according to ASTM C1437-15 [20]. A Haegermann cone of 100 mm lower diameter, 70 mm upper diameter and 50 mm height was compacted in 2 layers and smoothed by trowel. The mould was removed and the table was immediately dropped 25 times in 15 s. The diameter of the mortar is then recorded.

3 Results and Discussion

3.1 Shear Vane Test

As previously mentioned, concrete mixture properties change due to thixotropy and hydration and structural development increases yield stress with time. The shear vane test was performed on samples at regular intervals of 10 min to characterize this development. The shear strength could not be measured for mixes 3 and 6 after 40 min as they exceeded the capacity of the shear vane apparatus.

Figure 1 shows the evaluation of shear strength over the setting time, and the increase with setting time is clear. This could be attributed to the development of network bonds and hydration over time [18]. The initial setting time is influenced by van der Waals attractive forces between ettringite and nanoclay, while subsequent changes over time are due to hydration mechanisms with the development of hydrates (e.g. Aft and C-S-H gel) being the main components [21].

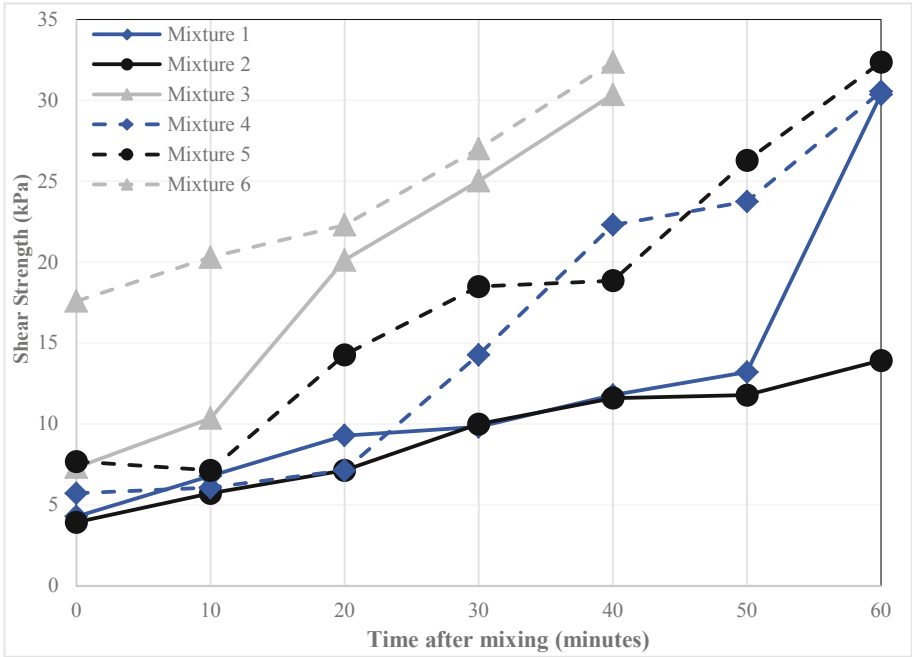


Fig. 1. Evaluation of shear strength over the setting time.

Experimental results showed that increasing the percentage of superplasticizer could reduce the development of shear strength over time.

Experimental results have also shown that adding 0.5 wt.% nanoclay increases the initial shear strength of the concrete by 186% in presence of 0.2 wt.% superplasticizer and by almost 310% in the presence of 0.4 wt.% superplasticizer (Fig. 2). This was also confirmed in previous studies [8] when addition of 0.5 wt.% nanoclay increases the yield stress of the mixes 3 times. Rahul et al. [2] also noticed an increase in yield stress with the addition of nanoclay. As nanoclay closes and compacts pores in the concrete, the initial shear strength is expected to increase [10]. Furthermore, the ettringite, which formed within 10 min of initial water and cement contact, carries a positive charge; nanoclay particles carry a negative charge at the edges and Kawashima et al. [21] has suggested that these particles are flocculating. This high yield stress allowed higher buildability and lower deformation of the mixes during the printing process [22]. As previous research [2] has shown, mixes with initial shear strength of 1.5–2.5 kPa are

appropriate for specific types of concrete 3D printers. Above this range the extrudability of the material was difficult. Le et al. [3] recommended a lower shear strength of 0.3–0.9 kPa as an appropriate range. This could be because of the smaller nozzle size. Le et al. [3] used a 9 mm diameter circular nozzle compared to Rahul et al. [2] who used a rectangular nozzle size of 30×20 mm. It is likely however that nozzle size has considerable influence on the reported extrudability of the concrete.

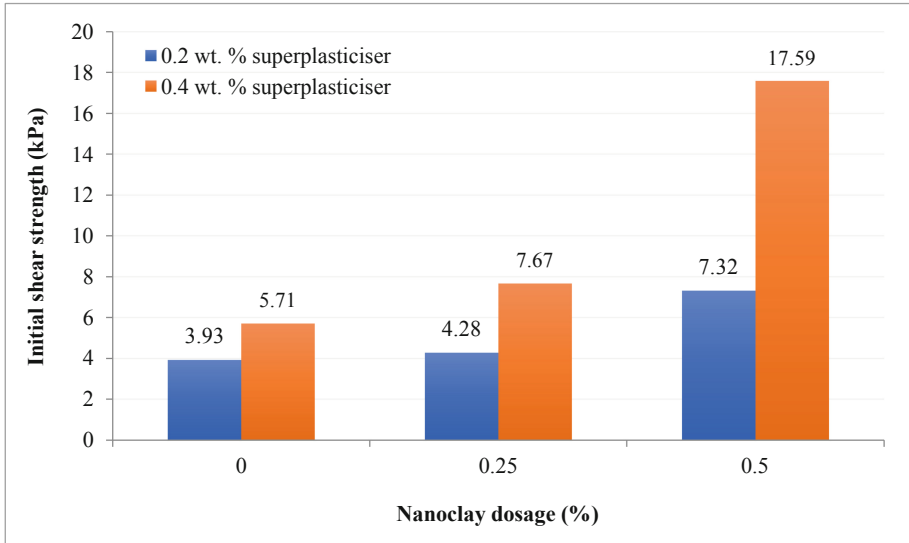


Fig. 2. Effect of nanoclay dosage on the initial shear strength of mixes.

The results also showed that increasing the percentage of superplasticizer increased the initial shear strength of mixes. Increasing the dosage of superplasticizer from 0.2 wt.% to 0.4 wt.% could result in a 200% increase in initial shear strength.

3.2 Compressive and Flexural Strength

The results of the compression and flexural testing after 7 days are presented in Table 3. The experimental results showed that the use of nanoclay reduced the compressive and flexural strength of all mixes. Although some previous researches [8, 13, 22] reported an improvement in the mechanical properties of mixes with the addition of nanoclay, the data below suggests otherwise. This however is in agreement with Panda et al. [4] who reported a 17% reduction in compressive strength with addition of 0.5 wt.% of the same nanoclay. Heikal and Ibrahim [9] also mentioned a reduction in compressive strength by addition of 8 wt.% nanoclay as a result of agglomeration of nanoclay around cement grains which retard the cement hydration. The hydrophilic nature of the clay may have led to water absorption, which could retard the geopolymer reaction as reported in earlier research [4, 23].

Experimental results have also shown that increasing the dosage of superplasticizer from 0.2 wt.% to 0.4 wt.% decreased the compressive strength of the mixes.

Table 3. Results of compression and flexural tests.

Mixture	Compressive strength (MPa)	Flexural strength (MPa)
1	39.23	6.27
2	36.76	7.46
3	34.04	7.09
4	37.67	8.08
5	33.75	6.90
6	25.68	6.85

3.3 Slump Flow Test

The flow of each mixture is presented in Fig. 3. The slump flow values are related to the solid state of the dynamic yield stress and pumpability [24]. Experimental results show that the addition of nanoclay decreases the flow of the mixes. Similarly, Kazemian et al. [12] reported a significant increase in viscosity and cohesion of mixes and flow reduction by addition of 0.3% nanoclay to the mixes. This could be explained by reducing the initial and final setting times of cement paste with addition of nanoclay. Nanoclay increases the rate of hydration and activates the hydration reaction. The formation of excessive amounts of hydrated C-S-H, produced from pozzolanic reaction, fills some of the open pores which was initially filled with water and subsequently the setting time decreased [10].

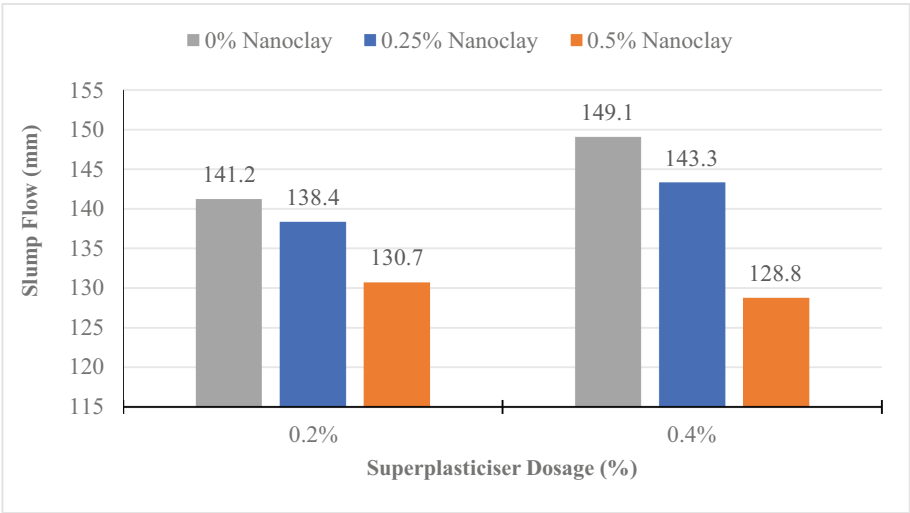


Fig. 3. Effect of nanoclay and superplasticizer dosage on the slump flow of the mixes.

Increasing the dosage of superplasticizer from 0.2 wt.% to 0.4 wt.% was also shown to influence the flowability of the mixes.

4 Conclusions

In this study the effect of nanoclay and superplasticizer on shear strength-based mixture design approach for 3D concrete printing was investigated. Nanoclay was added as a rheology modifier, but also strengthens the mixture by increasing the yield stress. Six different printing mixtures were developed, and slump flow, compressive and flexural strength and shear strength properties were measured. Experimental results showed the shear strength increased with nanoclay content. Increasing the dosage of superplasticizer also increased the initial shear strength of mixes. The addition of nanoclay had a negative influence on the 7-day strength development of mixes, and this was particularly pronounced for higher nanoclay content. Finally, the slump flow test results showed the addition of nanoclay decreased the flow of mixes. To summarize, our testing has shown that while the introduction of nanoclay has improved the buildability of the concrete mixes, it has also decreased their flowability.

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Digital Fabrication of ‘Just-Add-Water’ Geopolymers: Effects of Curing Condition and Print-Time Interval

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Abstract. A 3D-printable one-part geopolymer concrete has recently been developed by the authors of this study for construction automation applications. Instead of large amounts of alkaline solutions, a small amount of sodium metasilicate powder as the solid activator was used to formulate the ‘just-add-water’ geopolymer binder. Development of such 3D-printable concrete tackles the challenges associated with handling of hazardous activator solutions and enhances the commercial viability of using geopolymer as a sustainable binder for 3D-printable concretes. This paper presents the effects of curing conditions (i.e. curing temperature and curing time) and the print-time interval on the properties of the developed printable concrete. Workability, setting time, static yield stress evolution of the mixture were measured. In addition, compressive strength and flexural strength in different loading directions, as well as the inter-layer strength of the printed specimens were measured. According to the results, the compressive and flexural strengths of the specimens printed with different delay times were comparable in all loading directions. In addition, the compressive and flexural strengths of the printed specimens subjected to 28 days of ambient temperature curing were higher than those of the counterpart heat cured specimens. Furthermore, the static yield stress of the fresh mixture increased linearly for up to 60 min of rest time.

Keywords: 3D concrete printing · One-part geopolymer · Solid activator · Mechanical properties · Curing · Print-time interval

1 Introduction

The binder used in many of the currently available 3D-printable concretes is ordinary Portland cement (OPC) [1, 2]. As a sustainable alternative to OPC, the authors of this paper have been working to use geopolymers to develop extrusion-based 3D-printable concretes. Geopolymer can be manufactured by alkali activation of aluminosilicate source materials such as fly ash and slag.

At first, the authors developed a 3D-printable heat cured two-part geopolymer concrete using 100% fly ash as the only source material and a combination of sodium silicate and sodium hydroxide solutions as the activator [3]. The influence of different

types of fibers (namely polyvinyl alcohol (PVA), polypropylene (PP) and polyphenylene benzobisoxazole (PBO) fibers) on the hardened properties of the developed printable fly ash-based geopolymers was investigated. The results showed that inclusion of 0.25% (by volume) of fibers reduced the inter-layer bond strength of the specimens in the range of 15% to 23%, depending on the type of fiber. However, the flexural strength of the specimens containing only 0.25% (by volume) of fibers significantly increased in the range of 17% to 34%, depending on the type of fiber. Among the fibers investigated, the PBO fiber was the most effective type of fiber in enhancing the flexural strength, while the PVA fiber led to the lowest reduction in the inter-layer bond strength [3]. In addition, the authors also investigated the influence of PP fibers addition on the fresh and hardened properties. The results showed that inclusion of PP fibers enhanced the shape-retention-ability, compressive and flexural strengths of the specimens. Deflection-hardening behavior was observed in the specimens containing 0.75% and 1.0% (by volume) of PP fibers [4].

The necessity for heat curing for the developed 3D-printable two-part fly ash-based geopolymers can limit its on-site application. The authors overcome this problem by developing a 3D-printable two-part geopolymer that can be cured at ambient temperature, in which fly ash was partially replaced by slag. The results showed that the type of activator had a significant effect on both fresh and hardened properties of the printed two-part ambient temperature-cured geopolymer concrete. Among the activators investigated, a combination of sodium hydroxide and sodium silicate with a modulus ratio (M_s) equal to 3.22 (where $M_s = n\text{SiO}_2/n\text{Na}_2\text{O}$) was the most effective activator [5].

Handling of large amounts of alkaline solutions, which are often viscous, is difficult and challenging, which in turn can limit the large-scale and wide-spread application of the developed 3D-printable two-part ambient temperature-cured geopolymer concrete. To tackle this problem, the authors of this paper, for the first time, developed a 3D-printable one-part ambient temperature-cured geopolymer concrete, in which a small amount of anhydrous sodium metasilicate powder was used as the solid activator [6]. In the authors' previous publication [6], the hardened properties of the developed 3D-printed one-part geopolymer concrete subjected to heat curing were reported. As a follow-up study, this paper reports the effect of curing conditions (i.e. curing temperature and curing time) and print-time intervals on the fresh and hardened properties of the developed 3D-printable one-part geopolymer concrete.

2 Experimental Procedures

2.1 Materials and Mixture Proportions

The mixture proportions were adopted from the authors' previous study [6]. The geopolymer source materials were composed of ground granulated blast furnace slag (50 wt.%) and low-calcium (Class F) fly ash (50 wt.%). The slag and fly ash were supplied by Building Products Supplies Pty Ltd., Australia and Gladstone power station in Queensland, Australia, respectively. As the solid activator, anhydrous sodium metasilicate powder with a modulus ratio (M_s) equal to 0.9 (where $M_s = n\text{SiO}_2/n\text{Na}_2\text{O}$,

$\text{SiO}_2 = 46 \text{ wt.}\%$ and $\text{Na}_2\text{O} = 51 \text{ wt.}\%$) supplied by Redox, Australia was used. The mass ratio of the solid activator to the source materials was 0.08:1.0. Two different sizes of silica sands were used in this study. The relatively coarser sand had a $D_{50} = 896 \mu\text{m}$, while the relatively finer sand had a $D_{50} = 172 \mu\text{m}$. The mass ratio of the coarser sand to the finer sand was 1.0:0.5. The mass ratio of the total sands to the source materials was 1.5:1.0. The mass ratio of water to the source materials was 0.34:1.0.

2.2 Mixing, Printing and Curing

Firstly, all solid materials were dry mixed in a 20 L Hobart mixer for approximately two min. Then, tap water was slowly added to the dry materials and the mixing process was continued for further 10 min to achieve a consistent mixture.

A custom-made small-scale 3D printer equipped with a piston-type extruder was used in this study. Details of the printer and the printing procedure can be seen in [5, 7]. In this study, the effects of print-time intervals between layers (also known as delay time) on the properties of printed geopolymer were investigated. Two-layer filaments were printed with two min and 15 min delay times. The dimensions of the printed two-layer filaments were $200 \text{ mm} \times 30 \text{ mm} \times 30 \text{ mm}$ ($L \times W \times H$).

The effects of curing condition (i.e. curing temperature and curing time) on the properties were also investigated. All printed specimens were sealed in a container to avoid moisture loss during the curing process. The printed specimens were divided into two groups for different curing conditions. One group was cured in an oven at 60°C for 24 h, while another group was cured in the laboratory at ambient temperature ($23^\circ\text{C} \pm 3^\circ\text{C}$) for seven and 28 days.

2.3 Testing

The workability of the fresh mixture was determined immediately after mixing by conducting a flow table test in accordance with ASTM C1437 (2015). The initial and final setting times of the fresh mixture were determined by using a Vicat apparatus in accordance with ASTM C807 (2018).

Following [8], the static yield stress of the fresh geopolymer mixture was determined via measuring the penetration depth of a cone plunger (with a tip angle of 30°) in the fresh mixture.

To measure compressive strength of the printed geopolymer, 30 mm cube specimens were sawn from the $200 \text{ mm} \times 30 \text{ mm} \times 30 \text{ mm}$ printed specimens and tested in X, Y and Z directions (Fig. 1a). A minimum of six specimens were prepared for each loading direction. The compressive strength was measured at a load rate of 20 MPa/min .

The flexural strength of the printed geopolymer was measured by testing $200 \text{ mm} \times 30 \text{ mm} \times 30 \text{ mm}$ printed specimens in a three-point bending test setup with a 150 mm long span at the rate of 1.0 mm/min . A minimum of three specimens were prepared for each loading direction. The flexural strength of the printed geopolymer was measured in Y and Z directions (Fig. 1b). It should be noted that the surfaces of the printed specimens were ground to have a smooth and flat surface before conducting compressive and flexural tests.

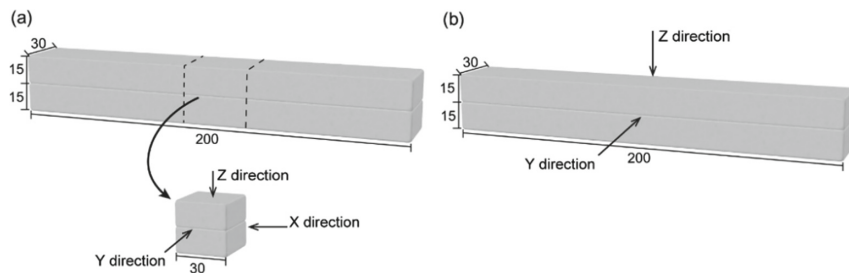


Fig. 1. Cutting diagram and testing directions for (a) compression and (b) flexural tests of printed ‘one-part’ geopolymer. All dimensions are in millimeter.

The interlayer bond strength of the printed geopolymer was measured by loading the printed specimens in uniaxial tension. The 50 mm × 30 mm × 30 mm (L × W × H) specimens were sawn from the printed filaments. A minimum of six specimens were prepared for each delay time. Two metallic T-sections were attached on the top and bottom of the specimen by an epoxy resin. The test was conducted at a rate of 1 mm/min. Details of the test can be seen in [5, 7].

3 Results and Discussion

3.1 Workability and Setting Time

The average spread diameters of the fresh mixture were 105 mm and 177 mm, before and after dropping of the flow table, respectively. Considering the bottom diameter of the mini-slump cone used in this study was 100 mm, the spread diameter of 105 mm before dropping of the flow table indicates that the fresh geopolymer had almost a zero-slump mixture, which is desirable for the extrusion-based 3DCP process.

The initial and final setting times of the fresh mixture were 65 min and 152 min, respectively. However, the open time of the fresh mixture was determined to be about 20 min, which was much shorter than the measured initial setting time (65 min). The end of open time was determined when the mixture was difficult to be extruded from the nozzle or tearing was observed on the extruded filaments.

3.2 Static Yield Stress Evolution

Figure 2 presents the static yield stress evolution of the fresh mixture. The static yield stress linearly increased for up to 60 min of rest time. Lecompte and Perrot [9] studied the yield stress of OPC paste with different water to cement ratios and found that the yield stress evolution of the mixture with higher degrees of cement hydration linearly increased for up to about 70 min of rest time and then exponentially increased. Similar to OPC-based mixture, the yield stress evolution of geopolymer mixture is significantly influenced by the mixture parameters (e.g. slag content and type and dosage of activator) as these parameters can influence the rate of geopolymerisation process, inter-particle adhesion forces and mechanical interlock between particles [10].

The static yield stress evolution of the printing material is essential to prevent the printed object from collapsing due to inadequate strength of the bottom layer to support the weight of upper printed layers [11]. Following [11], the stress induced by the weight of subsequent layers with 2 min and 5 min delay times were calculated and showed in Fig. 2. Regardless of the delay time, the measured static yield stress of the fresh mixture was always higher than the calculated stress induced by the deposited layers. Therefore, it can be expected that the printed object does not collapse due to inadequate strength of the bottom layer to support the weight of upper printed layers when it is printed with at least 2 min delay time.

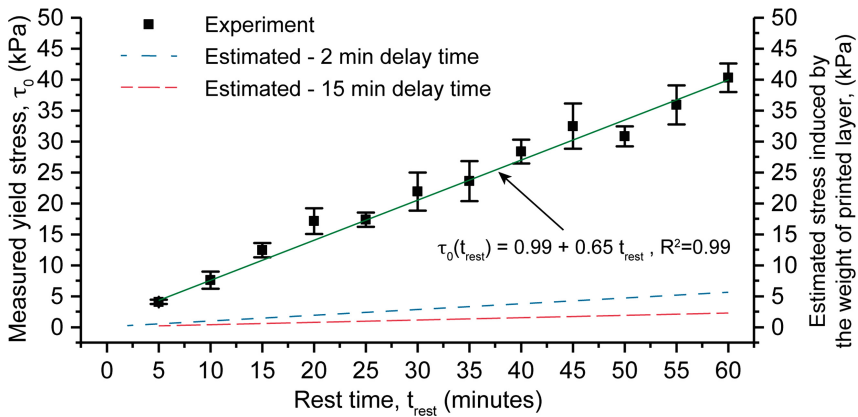


Fig. 2. The static yield stress evolution of the fresh 3D-printable geopolymer mixture.

3.3 Compressive Strength

Figure 3 presents the compressive strength results. Similar to other studies on printable OPC and geopolymer concrete [1, 5, 7, 12], an anisotropic behavior was found in the compressive strength results, depending on the testing direction. This is true irrespective of the curing temperature, curing time and delay time. As shown in Fig. 3, the lowest compressive strength was consistently obtained in Y direction, while the highest compressive strength was in X direction. The same pattern was obtained in the authors' previous studies on printable two-part geopolymer mortar [5] and OPC mortar [7] and the underlying reasons for this pattern are well explained.

As expected and shown in Fig. 3, depending on the delay time, the 28-day compressive strengths of the printed specimens in X, Y and Z directions were 38–41%, 27–35% and 47–54%, respectively higher than that of the printed specimens cured for 7 days. This is because of continued geopolymerisation reaction as the curing time increased. It should be pointed out that the 28-day compressive strength of the ambient temperature cured specimens was higher (up to 23%) than that of the heat cured specimens. This shows the possibility of using the 'just-add-water' geopolymer mixture developed in this study to print building components without the need for the heat curing, which is particularly beneficial in terms of reduction in cost and environmental impacts (carbon emissions and energy consumption).

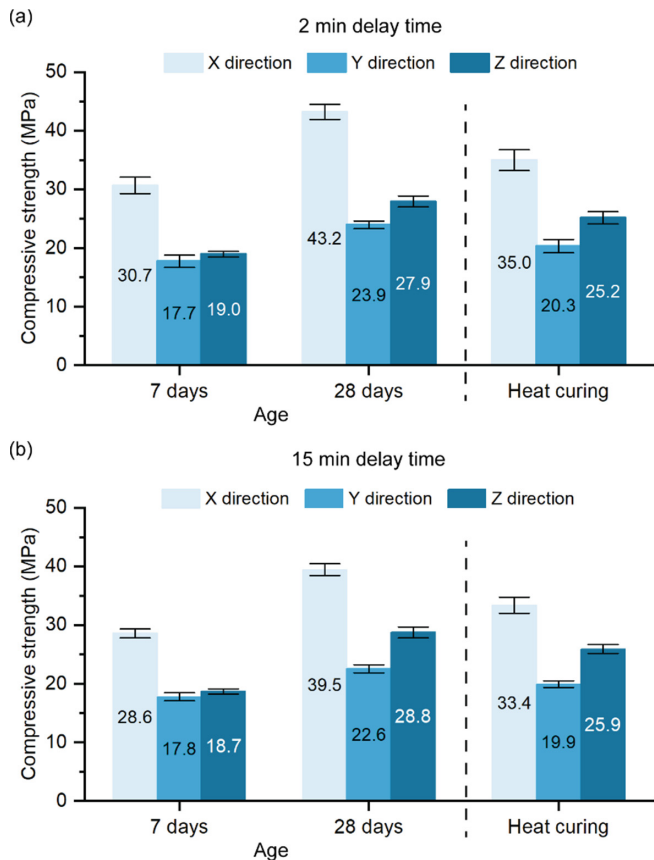


Fig. 3. Compressive strength of the 3D printed geopolymers with (a) 2 min and (b) 15 min delay times. Note: Heat curing results adopted from Nematollahi et al. [6].

As can be seen in Fig. 3, the compressive strengths of the geopolymer specimens printed with two different delay times were comparable in all loading directions. This is true irrespective of the curing time and curing temperature. Therefore, it can be said that the delay time had an insignificant effect on the strength of the printed geopolymer under compression.

3.4 Flexural Strength

Figure 4 presents the flexural strength results. The printed geopolymer specimens also exhibited anisotropic behavior in flexure, depending on the loading direction. This is true irrespective of the curing conditions and delay time. As can be seen in Fig. 4, the flexural strength in Z direction was always higher than that in Y direction for all curing times, curing temperatures and delay times. This pattern is consistent with the compressive strength results obtained in this study. In addition, these results are also in good agreement with the previous studies on 3D-printable two-part geopolymer- and

OPC-based materials [5, 7, 12, 13]. The bottom layer of the specimen was mostly well compacted as compared to the top layer because of the self-weight of the top layer. Thus, the flexural strength in Z direction was higher than that in Y direction [7].

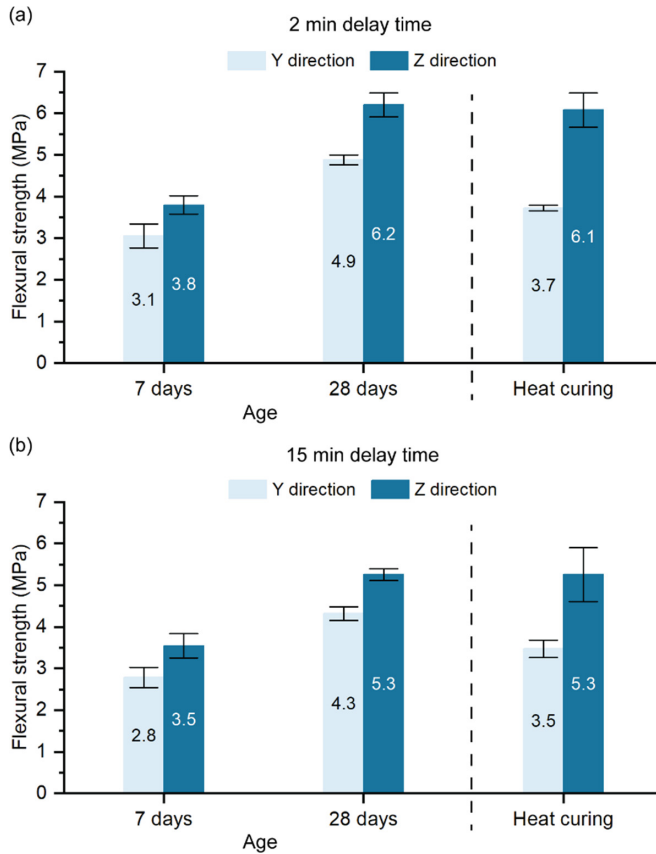


Fig. 4. Flexural strengths of the 3D printed geopolymer with (a) 2 min and (b) 15 min delay times. Note: Heat curing results adopted from Nematollahi et al. [6].

As expected and similar to the compressive strength results, depending on the delay time, the 28-day flexural strength of the printed specimens in Y and Z directions were 54–58% and 51–63% respectively higher than that of the printed specimens cured for seven days. According to Fig. 4, the 28-day flexural strength of the ambient temperature cured samples was up to 32% higher than that of the heat cured specimen. This is consistent with the compressive strength results.

As shown in Fig. 4, when compared to the specimens with two min delay time, the mean flexural strength of the specimens with 15 min delay time was 6–17% lower, depending on the testing direction, curing time and curing temperature. However, it can be argued that the differences were within the scatter of the results. Therefore, it can be

concluded that, similar to the compressive strength results, the delay time did not have considerable effect on the strength of the printed geopolymer under flexure.

3.5 Inter-layer Strength

Figure 5 presents the interlayer strength results. The 28-day interlayer bond strength of the printed specimens was about 1.5–2.3 times higher than that of the specimen cured for seven days, depending on the delay time. This significant increase of the interlayer strength due to longer curing period was also reported in the authors' previous study on 3D printed ambient temperature cured 'two-part' geopolymer [5]. The increase in interlayer strength due to longer curing time is consistence with the flexural and compressive strength results, in which the strength was also increased with longer curing time.

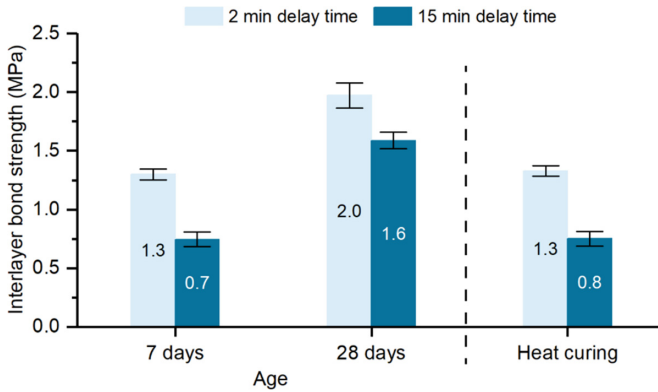


Fig. 5. Interlayer bond strengths of the 3D printed geopolymer with different delay times and curing conditions. Note: Heat curing results adopted from Nematollahi et al. [6].

According to Fig. 5, the 28-day inter-layer strength of the ambient temperature-cured specimens was 54–100% higher than that of the heat cured specimens, depending on the delay time. As expected, the inter-layer bond strength of the specimens with two min delay time was 25–86% higher than that of the specimens with 15 min delay time, depending on the curing temperature and curing time. This is understood as the bond between new and old printed layers reduces as the delay time increases. Several studies also reported that the inter-layer bond strength decreased as the delay time increased [1, 12, 13]. It is interesting to note that at 7 days the inter-layer strength of the specimens with two min delay time was 86% higher than that of the specimens with 15 min delay time. However, at 28 days the inter-layer strength of the specimens with two min delay time was only 25% higher than that of the specimens with 15 min delay time. Therefore, it can be said that as curing time increased from seven days to 28 days, the difference between the inter-layer strength results due to different delay times reduced significantly.

4 Conclusions

In this study the properties of a 3D-printable 'just-add-water' geopolymer concrete were reported. The specimens exhibited the compressive strength of 17.7–43.2 MPa, the flexural strength of 2.8–6.2 MPa and the inter-layer strength of 0.7–2.0 MPa, depending on the curing temperature, curing time and delay time. The following main conclusions are drawn:

- 1) Regardless of the testing direction, curing time and curing temperature, the investigated delay times (i.e. two min and 15 min) did not have considerable influences on the compressive and flexural strengths of the specimens. However, the inter-layer strength of the specimens printed with two min delay time was 25–86% higher than that of the specimens printed with 15 min delay time, depending on the curing conditions. The heat curing (at 60 °C for 24 h) introduced significantly higher reduction (63%) in the inter-layer strength of the specimens printed with the longer delay time, as compared to that of the specimens cured at the ambient temperature for 28 days (25%).
- 2) The 28-day compressive, flexural and inter-layer strengths of the ambient temperature-cured printed specimens were up to 23%, 32% and 100%, respectively higher than those of the counterpart heat cured specimens, depending on the delay time and testing direction. It can be said that the ambient temperature curing regime is particularly beneficial in terms of achieving superior mechanical properties and reduction in cost and environmental impacts associated with the heat curing regime.

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Advances in Binder-Jet 3D Printing of Non-cementitious Materials

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Abstract. Additive Manufacturing techniques enable an unprecedentedly fine-grained control over the material they process, both in terms of its geometric distribution and its very composition. With the rapid development of printing methods suitable for the production of large-scale objects together with their respective material systems, applications in the construction industries showcase an expanding portfolio of practical examples. However, considering the more and more critical demand for minimizing the environmental impact due to construction activities, the aim for mechanical stability of a material system is no longer sufficient and needs to be flanked by attentive considerations over the sustainability of its components.

The presented research investigates to which extent cement can be either accompanied or replaced by more sustainable material sources, with specific focus on geopolymer and its application in the production of stay-in-place, self-supporting and waste-free formwork systems for modular building components. The manufacturing technique considered for such investigation is binder jet 3d printing, on the basis of the remarkable flexibility it offers in terms of material processing workflow. Three selected material systems, each one introducing recycled and/or repurposed byproducts of different industrial processes (such as stone cutting and demolition activities), will be evaluated and benchmarked against the output of commercially available organic-based BJ systems.

Finally, a brief overview of the prototypical binder jet printing setup specifically developed for material testing at construction-scale will be presented, mainly focusing on the control parameters that have a larger impact on the overall properties of printed output.

Keywords: Binder jetting · Construction-scale · Geopolymer · Manufacturing process · Waste-free · Direct printing

1 Introduction

The construction industry is responsible for the consumption of more than 40% of the resources worldwide [1], and its activities entail dispersion in the atmosphere of considerable amounts of CO₂. Moreover, the availability of heavily exploited construction materials such as sand and gravel is becoming more and more challenging in different parts of the world [2, 3]. Additive Manufacturing (AM) techniques open new

possibilities to tackle both problems: by enabling the production of otherwise non-renderable geometries, design techniques can be implemented for minimizing material consumption in the production of both building components and formworks [4, 5]. At the same time, by allowing the precise characterisation of the utilized materials within the object of production [6], new material systems can be developed and applied, potentially allowing for alternative sources to reduce the stress posed on more conventionally adopted ones.

AM lists a variety of different techniques, characterized by the materials in use and the way they are processed. Among these, the most promising processes in the context of construction are currently Concrete Extrusion [6] and Binder Jet 3D Printing (BJP): the former features a remarkable printing speed and, by deploying the most used material in the history of construction, sits at the valuable intersection between innovative and trustworthy. However, the inherent limits in terms of renderable geometries pose relevant constraints to the aforementioned design freedom, and the process itself presents nontrivial challenges for syncing the setting time of the concrete mix and the printing time of a single layer. With BJP, on the other hand, these limitations can be overcome [7].

In BJP, consecutive sections are bonded to form the object of design: as the loose powder supports the printed parts throughout the whole process, any geometric features can be achieved without the need of additional support (Fig. 1).

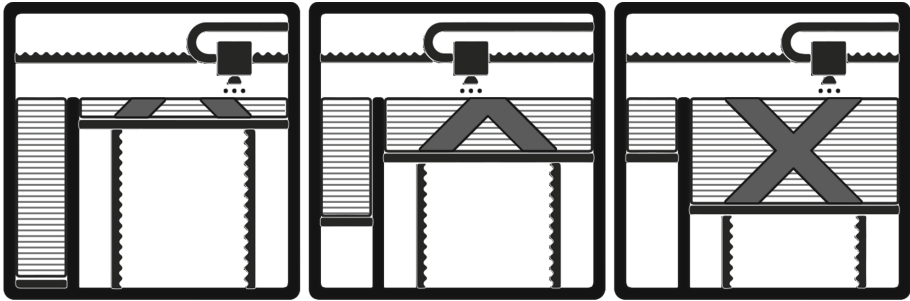


Fig. 1. Example of Binder Jet 3D printing: the previously deposited material supports the printed parts throughout the whole process.

Moreover, the same supporting action eases the transition between consecutive layers, allowing the setting time of each section to be less critical in the overall timing of the process. Finally, and most importantly for the scope of this paper, the process allows for virtually any bulk material to be used as part of the material system.

Commercial BJP setups make use of organic resins to bind mono-sized silica sand: this material system allows for production of high precision parts (up to 1200 dpi) in submillimeter layers ($\leq 500 \mu\text{m}$). However, the brittle behavior of the printed parts and their release of volatile organic compounds (VOC) during and after production [8] significantly limits the range of possible applications.

In previous work we showed that the process of BJP can be modified for enabling the use of alternative binders, namely a geopolymer [9]. Geopolymers are inorganic amorphous materials often used in construction as a cement replacement and for fire resistant coating [12, 13]. Implemented as a binding compound, geopolymers can significantly reduce the CO₂ emissions of the printing process [10].

The presented paper documents how the inert material (silica sand) can be replaced by recycled and locally available sources. The following materials are evaluated: Gneiss sand, a byproduct from quarries in the Canton Ticino, and two recycled construction materials, namely brick powder and crushed concrete powder, sourced from demolition sites within Switzerland.

2 Methods and Materials

2.1 Mix Design for Material Comparison



Fig. 2. Test bars printed with different material systems: Gneiss sand, Concrete sand and Brick sand (from bottom to top).

The geopolymer binding compound developed for this research consists of two components: a liquid activator, selectively dispensed through a tapered nozzle (diam. 200 μm), and a solid binder, premixed with the aggregates and distributed over the print platform. The solid component of the binder in use is Metakaolin, distributed from Imerys with the product name of Metastar 501, mean grain size d_{50} of 4 μm . Additional information can be found in reference [11]. For the three mixes, the same weight percentage is applied (Table 1).

Table 1. Material mixes.

#	Aggregate wt%	Binder wt%	Activator
1	Gneiss sand, 80 wt%	Metakaolin, 20 wt%	Potassium silicate
2	Brick sand, 80 wt%	Metakaolin, 20 wt%	Potassium silicate
3	Concrete granulate, 80 wt%	Metakaolin, 20 wt%	Potassium silicate

The process relies on the full penetration of the liquid phase into the printed layer for building up a consistent bond throughout the volume. The penetration rate is affected by many factors, including the composition of the binding solution, the configuration of the printing setup and the grain-size distribution of the powder pack.

In previous tests we verified that, given the other interdependent dimensions (described in Sects. 2.2 and 2.3), an acceptable penetration rate can be achieved using aggregates with grain-sizes in the range of 0–1.5 mm. Therefore, all the materials have been sieved accordingly.

The composition of the activator component of the binder is not in the scope of the current paper: for detailed information one can refer to previously published documents [9]. From previous tests it resulted that the optimal sand to activator volume ratio ranges between 0.3 and 0.4.

2.2 Prototypical Setup Configuration

As previously mentioned, commercial BJP 3D printers implement InkJet technology for dispensing the binding solution: featuring drop sizes in the range of 10–100 picolitres (10^{-12} l), such technology allows for high resolution prints (up to 1200 dpi). However, the limited volume throughput is not suitable for materials with larger granulometry (usually limited to 250 μ m), and the strict specification of the liquid characteristics each printhead can deliver significantly limits their usability in a testing environment.

For these reasons, a prototypical testing setup was developed and used for material research. The system is composed of three linear axes and a set of components for carrying out the routines necessary for the printing process. The components of interest in the context of the current document are illustrated in Fig. 3.

Pumping System. To overcome the limitations of InkJet printheads in terms of volume rate and compatible substances, a peristaltic pump is installed for distributing the binding solution.

Whereas not able to reach resolutions as high as InkJet technology, this system offers a minimal amount of wetted components, allowing for inexpensive testing routines. The implemented model features a double roller head, each counting 16 rollers, offering a large range of volume flow rates and significantly reducing the flow pulsation. The specific model is produced and distributed by Spetec GmbH.

Sand Spreading System. In order to allow for a large range of grain-sizes to be distributed over the print platform, a tailored distribution system was designed.

The flow of particles is controlled through an electronically controlled pneumatic shutter and allows granulometries up to 12 mm. The planarity of each layer is obtained by operating a counter-spinning roller spanning below the gantry. The compacity of the printing bed can be fine-tuned by setting the rotational speed and adjusting the vertical offset during the recoating operation.

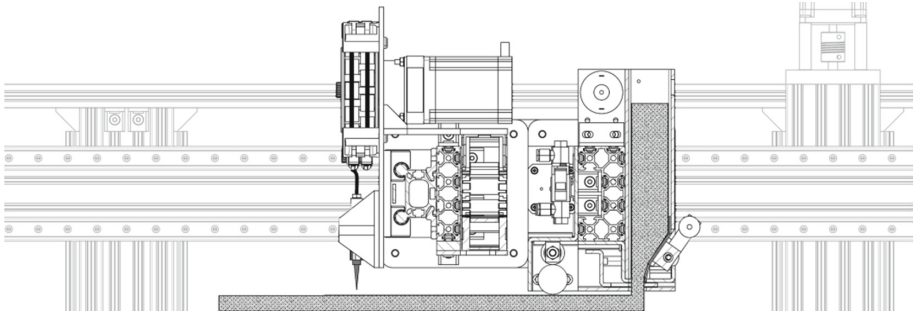


Fig. 3. Main components of the BJP setup used (from left to right): anti-pulse peristaltic pump, compacting roller, sand spreading system (pneumatic actuated shutter)

2.3 Process Parameters

The 3D printer used throughout the tests allows for granular control over many different process parameters: the most relevant in this context are listed in Table 2.

Table 2. Process parameters.

Parameter	Min.	Typ.	Max	Unit
Binder density		1.45		g/cm ³
Binder viscosity		6		mPas
Linear speed (print)	100	200	250	mm/s
Linear speed (recoat)		25		mm/s
Nozzle diameter	150	200	250	μm
Tubing I.D.		635		μm
Binder volume per revolution	50	75	101	μl/rev
Binder volume per unit of length	0.2	0.7	1.0	μl/mm
Layer thickness	1.8	2.5	3.5	mm
Line spacing	300	750	1200	μm
Ejection speed		3250		mm/s

For all the tests hereby presented, the values listed in the central column (typ.) have been assigned to the respective parameters. All the specimens were removed from the print box 48 h after the completion of the printing process.

2.4 Mechanical Testing Strategy

Three prisms with a targeted size of $160 \times 40 \times 40$ mm were printed with each material combination. After 7 days of curing at room temperature, the samples were tested in a mechanical press (Unitronic, Matest) using a 50 kN cell, applying 0.1 kN/s.

The dimensions of all the prisms were measured along the x, y and z direction (cf Table 3). The geometric accuracy was determined as in Eq. 1 and noted in Table 4. As the specimens did not present perfectly planar surfaces, the maximum measured dimension has been taken into consideration.

$$Accuracy [\%] = (measured\ size - targeted\ size) \div targeted\ size * 100 \quad (1)$$

The flexural strength of the specimen was first evaluated through three-point bending test; the resulting two segments of each prism were then tested in compression, respectively parallel and perpendicular to the printing direction. The results are documented and discussed in Sects. 3 and 4.

3 Results

3.1 Compressive Strength

The printed samples show a significantly different compression strength for the three tested material systems. On the other hand, the results indicate isotropic behavior, showing results almost unaltered by the testing direction.

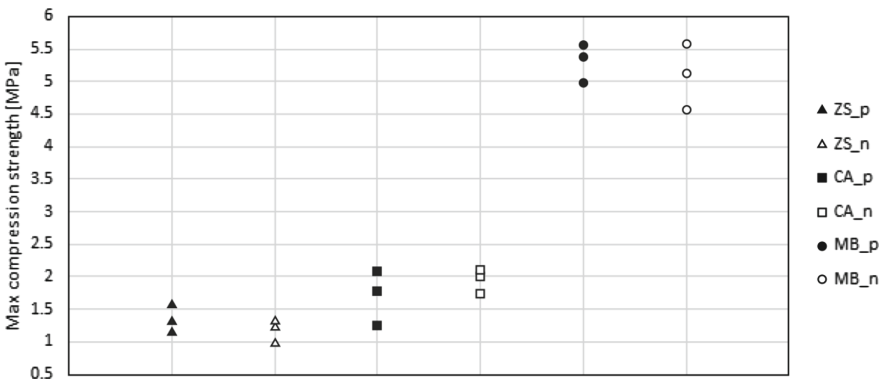


Fig. 4. Compression strength comparison: ZS = Brick Sand, CA = Concrete Aggregates, MB = Gneiss Sand, the suffixes p and n indicate the testing direction in relation to the printing direction, respectively parallel and normal

3.2 Flexural Strength

Similarly, to the compression test, the samples printed in Gneiss performed better than the other two analyzed materials.

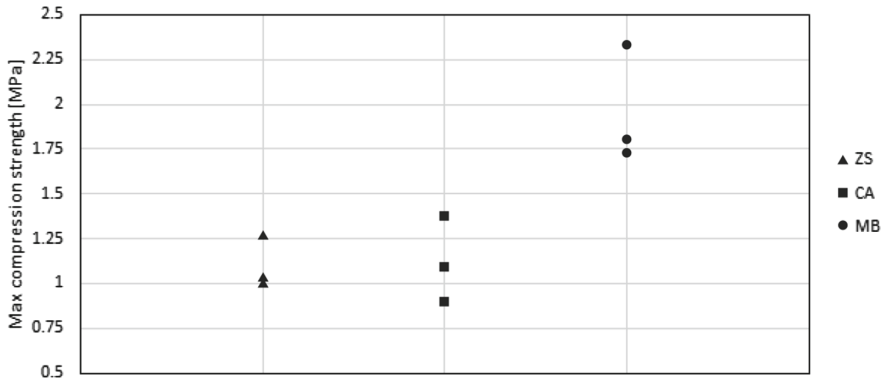


Fig. 5. Flexural strength comparison: ZS = Brick Sand, CA = Concrete Aggregates, MB = Gneiss Sand

3.3 Dimensions

All the printed samples show a dimensional accuracy consistent with the maximum grain size (1.5 mm) of the material in use (*cf.* Table 3), and no remarkable difference has been observed between the samples printed with different materials (*cf.* Table 4).

Table 3. Dimensions and standard deviation of the printed samples.

Material	x [mm].	y [mm].	z [mm]
Brick sand	160 ± 0	42 ± 1	41 ± 0
Concrete aggregates	160 ± 1	42 ± 0	41 ± 1
Gneiss sand	162 ± 2	42 ± 1	42 ± 0

Table 4. Accuracy of the printed samples (Eq. 1).

Material	x [%]	y [%]	z [%]
Brick sand	0.00	5.75	2.50
Concrete aggregates	0.18	5.00	1.50
Gneiss sand	0.00	5.83	2.50

The most notable difference between the tested materials resides in the resulting density of the printed samples (Fig. 6).

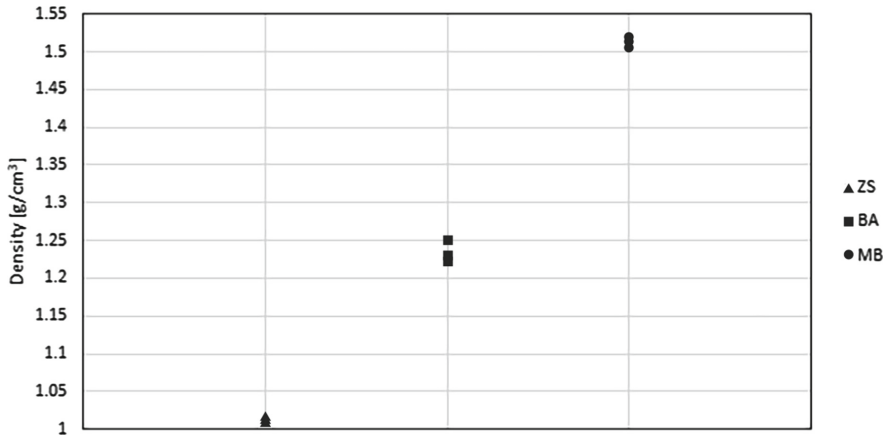


Fig. 6. Density comparison: ZS = Brick Sand, CA = Concrete Aggregates, MB = Gneiss Sand

4 Discussion

The results here presented support the following observations.

The compressive strength of the printed object is not affected by the orientation of the layers. The samples were tested both parallel and perpendicular to printing direction, and the comparison does not show notable differences (Fig. 4).

The mechanical response, in terms of both compressive and flexural strengths, increments proportionally to the resulting density of the sample. Beside the properties intrinsic to the material, the large deviation measured in the weight (± 74 g over an average of 354 g) can be explained by the grain size distribution of the different material batches. Further research will be conducted for characterizing the material mixes in order to improve the packing configuration without negatively affecting the penetration rate.

The geometrical rendering of the output is not notably affected by the quality of its material, showing consistent dimensions, comparable resolution and edge sharpness regardless of the substrate used in the mix (Fig. 2).

The printing parameters adopted for the presented tests have been identified through previous iterations. The results have shown that the most effective value for the sand to binder volume ratio is ca. 3:1.

Moreover, the proportion between maximum grain-size and layer thickness has proved to be optimal in the ratio of ca. 1:2, similar to how it is usually found in commercial printers.

Finally, after further inspection, the lower dimensional accuracy along the y axis resulted to be due to a slight miscalibration in the linear axes of printing setup.

5 Conclusions

The technology of Binder Jet 3D Printing can provide a valid fabrication method for significantly reducing the ecological footprint of construction-related activities. By enabling the accurate production of complex geometries, BJP offers a cost-effective solution for implementing optimized structural designs, thus considerably reducing the material consumption of the production (Fig. 5).

The mechanical response shown by the specimen in other tests we published [14], where values between 10 and 14 MPa have been observed, meets the requirements for compression-only structures (Fig. 7).



Fig. 7. Comparison of printed component: the component on the left was printed out of recycled brick sand with the process presented in this paper, the one on the right was produced with an industrial printing setup out of PMMA. Design by Block Research Group (ETH Zurich)

Moreover, BJP can reintroduce in the production chain materials otherwise considered waste. The presented series of tests suggest that a part of the volume of material resulting, for instance, from demolition activities, can be directly reused for construction purposes.

If implemented at industrial scale, the impact of BJP on the costs of production, distribution and disposal of construction material can be remarkable.

Acknowledgments. Financial support by the Swiss National Fund (SNF) and the National Center for Competence in Research (NCCR) is gratefully acknowledged.

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Rubber-Cement Composites for Additive Manufacturing: Physical, Mechanical and Thermo-Acoustic Characterization

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Abstract. The purpose of this work is to study the possibility of modifying a 3D printable cement-based mix by adding recycled tire rubber (TR) particles to replace the mineral aggregates. This strategy aims to evaluate the variation of some physical-mechanical properties of the material (lightness, durability, vibration absorption, acoustic and thermal insulation), promoting the disposal of the waste tires and the reduction in the consumption of natural resources. The rubberized mixture, in addition to offering interesting properties in terms of engineering performances (fundamentally important in the construction sector), can be used in additive manufacturing in the production of “bi-functional” applications. “Bi-functionality” refers to the possibility of giving a component, specific properties dependent on both the material properties and morphological-structural features.

Several printing mixtures, obtained for partial or total replacement of mineral aggregates with two types of rubber fillers (rubber powder and rubber granules), have been developed. After proper printability tests, an extensive experimental campaign was performed on printable rubber-cement composites: physical characterization, morphological analysis, mechanical characterization and evaluation of acoustic and thermal insulation properties. The rubber aggregates preserve optimal rheological properties related to the printability of the mixture. Besides, the synergy between the two types of polymer fillers in the cement matrix results in some interesting physical and mechanical effects: ductility, plastic energy absorption, durability, acoustic damping, and thermal inertia.

Keywords: Extrusion-based additive manufacturing · Tire rubber fillers · Rubber-cement mixtures · Physical-mechanical properties · Sound transmission loss · Thermal insulation

The design and choice of a “printable” material are crucial aspects of the performances of the Additive Manufacturing (AM) process. It is not possible to identify a “universal” printing mix, as its composition is strictly dependent on the design of the printing apparatus and the physical-mechanical requirements that the final product will have to possess. The study of innovative and functional mixtures is taking on a key role in the

technological progress of the AM processes. Specifically, research is focused on identifying low environmental solutions for minimizing the consumption of natural resources and environmental pollution. One of the main eco-friendly approaches is the development of “green” cement materials: modified cement-based mixtures with polymer, metal or ceramic aggregates derived from industrial waste [1].

The purpose of this work is to study the possibility of modifying a cement-based printing mix (suitable for the extrusion-based process) by adding recycled tire rubber (TR) to replace the mineral aggregates. Recycling of waste tires is of paramount importance both economically and environmentally. Worldwide, the number of scrapped tires is constantly growing (550 million/year in the U.S.A. and 1billion/year in Europe) and the most commonly used strategies for their disposal are based on high-polluting industrial treatments. In this context, the use of recycled TR as an aggregate in cement mixtures can be an alternative and cheap recycling strategy [2]. Besides, as evidenced by several literature works [3, 4], rubber particles incorporated in the cement matrix can confer interesting engineering properties: deformability, vibration absorption, durability, and sound insulation. The above-mentioned works highlight the effect of the size of TR aggregates on the morphological, physical and mechanical properties. The finest fraction, obtained through cryogenic grinding, provide better homogeneity, compaction, and fluidity of the mixture, while larger particles (resulting from mechanical grinding) improve deformability and vibroacoustic performances.

For the development of rubberized printable mixtures, two types of polymer fillers were selected as a partial or total replacement of natural aggregates: rubber powder (RP) and rubber granules (RG). The work aims to evaluate the polymer fillers’ synergy and the effect of their size, on the rheological, physical, mechanical and thermo-acoustic properties of the material. The first part of the paper focuses on the design of rubber-cement mixtures and the evaluation of printability properties. The results of experimental characterization are then presented: physical properties, microscopical analysis, mechanical testing, thermal conductivity, and sound insulation measurements.

1 Raw Materials Properties and Mix Design

This section shows the physical and morphological properties of TR fillers used to obtain the rubberized mixtures. Next, the composition of the standard cement material and the rubber-cement composites is described.

1.1 Tire Rubber Fillers

RP and RG (provided by ETRA, European Tyre Recycling Association) were used as a partial and total replacement of the sand constituting the reference cement mixture. Preliminary characterization was performed on TR fillers: density measurements and granulometry. The density of rubber aggregates was evaluated by Micromeritics AccuPyc 1330 He-pycnometer, while particle size distribution was determined by Leica MS5 optical microscope. The results are shown in Table 1.

Table 1. Properties of rubber fillers used in this work.

Rubber filler	Grain size (mm)	Density (kg/m ³)
Rubber powder	0.5–1.1	1209 ± 2
Rubber granules	2.5–3.7	1195 ± 1

The discrepancy between the density values could be attributable to the presence of textile or metal residues that persist after the grinding and cleaning processes.

1.2 Mix Design of Rubber-Cement Mixtures

Rubber-cement formulations were obtained from a reference printable mixture (*Ref.*) developed and patented by INNOVAcrete®. The material consists of Type I Portland cement, 0–0.4 mm limestone sand, 0.35 w/c ratio and chemical additives in proper proportions: Silica fume, Calcium oxide (expansive agent), superfluidifying agent, and reducer additive. Four rubberized mixtures (*Mix.2*, *Mix.3*, *Mix.4* and *Mix.5*) were developed with increasing amounts of RP and RG partially and totally replaced with sand of the plain compound. The composition of each formulation is summarized in Table 2.

Table 2. Rubber-cement mixtures proportions.

Mix design	Ref. (Kg/m ³)	Mix.2 (Kg/m ³)	Mix.3 (Kg/m ³)	Mix.4 (Kg/m ³)	Mix.5 (kg/m ³)
Cement	800	800	800	800	800
Water	300	280	260	250	230
Sand	1100	550	0	0	0
Rubber Pwd.	0	150	300	150	75
Rubber. Gran.	0	0	0	160	240
Additives	152	152	152	152	152

In *Mix.2*, 50% by volume of sand was replaced with the same amount of RP. In *Mix.3*, the sand was totally replaced with RP. In *Mix.4*, sand was replaced by 50% RP and 50% RG. In *Mix.5*, sand was replaced by 25% RP and 75% RG. The water content has been varied to obtain similar rheology and extrudability. From Table 2, it can be observed that by increasing the percentage of TR decreases the water/cement ratio. Polymer aggregates are larger and more irregular than sand, which implies less water demand. This is an interesting aspect from an environmental point of view: polymer fillers maintain optimal rheological properties of the cement-based materials but reduce the water consumption for the mixtures preparation.

2 Testing Program

2.1 Printability Test and Sample Manufacturing

Printability tests were performed at the Mechanical Engineering Department of the Marche Polytechnic University (Italy). The printing system is based on COMAU 3-axis robotic equipped with a PVC tube ($\varnothing = 10$ mm) that acts as an extrusion nozzle. The printable material is contained in a cylindrical aluminum container kept moving by a vibrating platform. The mixture is pressured by a compressed air system that ensures a constant pressure (4 bar). The pressure promotes the release of the material from the tube and the deposition takes place on the printing surface.

To evaluate the print quality of the rubberized mixtures, $220 \text{ mm} \times 160 \text{ mm} \times 15 \text{ mm}$ slabs were printed. A 100% infill and linear print path were selected for slab extrusion. The iteration was repeated 6 times, corresponding to the number of layers of the printed object.

Next, the slabs were cut thorough diamond circular saw to extract 2 types of samples for characterization tests: $40 \text{ mm} \times 40 \text{ mm} \times 230 \text{ mm}$ beams (mechanical tests) and $48 \text{ mm} \times 42 \text{ mm} \times 22 \text{ mm}$ blocks (density measurements, optical microscopy analysis, thermal conductivity, and acoustic tests).

2.2 Bulk Density Measurements

Considering the regular shape of the block specimens, the bulk density (ρ) was obtained by dividing the mass of oven-dried samples (110°C for 48 h) into its geometric volume. For each formulation, ρ was computed as an average of the values obtained on four replicate specimens.

2.3 Optical Microscopy (OM) and Scanning Electron Microscopy (SEM)

Blocks specimens (four samples per mixture) were examined under a Leica MS5 optical microscope. Before the analysis, blocks were polished on a mechanical rotating disk with abrasive characteristics (180 grit carbide disk). The surfaces and cross-sections of the samples were photographed under 16x magnification and inspected to evaluate the influence of TR fillers on the porosity and microstructural characteristics (aggregates distribution, micro-cracks) of the cementitious materials. The images were processed using ImageJ software.

SEM analysis was used to investigate the fillers-cement matrix interface and the mixture homogeneity depending on the type of TR aggregate. Small rubber-cement fragments were coated with carbon conductive film in a vacuum coating machine to prevent the specimens from acquiring the charge during the experiment. Backscattered Electron (BSE) and Secondary Electron (SE) images were acquired using a TESCAN MIRA 3 FEG-SEM.

2.4 Mechanical Characterization: Compression and Four-Point Flexural Test

For each formulation, three beams were tested in four-point bending up to failure at the loading rate of 1 mm/min, with a span length of 180 mm, according to ASTM C348 standard test method [5]. The flexural test was performed using a Zwick-Roell Z010 machine with 10 kN capacity.

Compression tests were conducted according to ASTM C109/109 M [5]. The two leftover parts, of each broken specimens in bending, were cut and polished to obtain cubic specimens (50 mm side). The samples were tested in compression by a ZwickRoell Z150 machine with 150 kN capacity. The loading rate was set to 1 mm/min.

2.5 Acoustic Characterization: Sound Transmission Loss Measurements

Sound insulation properties of the rubber-cement samples were characterized by Sound Transmission Loss (STL) measurement, which is defined as follow (Eq. 1):

$$STL(dB) = Lp_i - Lp_t \quad (1)$$

where Lp_i and Lp_t are the incident sound pressure level and transmitted sound pressure level, respectively. STL depends on the frequency of the incident acoustic wave and measures the efficiency of material in limiting the passage of sound. The bigger the STL value, the better the acoustic damping properties.

The STL values were measured according to ASTM E1050-98 [6] by a two-microphone impedance tube (designed and built at the Materials Engineering Dep. of “Sapienza” University). The testing apparatus consists of two identical 500 mm-long PVC tubes with an internal diameter of 160 mm. Each tube is covered with a sound-insulating sheath to minimize acoustic leakage and avoid the influence of external noise during the experiment. The specimen is placed in a plastic sample holder and mounted in the middle area of the apparatus. A 30 W Behringer MPA30BT loudspeaker is used as the sound source and is placed inside a wooden acoustic box lined with absorptive material. A removable cap, covered with polyurethane foam, is placed at the tube end to minimize the effect of the reflected sound waves. Two identical condenser microphones (Behringer ECM8000) are employed for sound pressure measurements. One acoustic transducer is located in the upstream tube and the other device is placed in the downstream tube to record the incident (Lp_i) and transmitted (Lp_t) sound levels respectively. The distance between the microphones and the surface of the specimens is 100 mm. The setting of process parameters and acoustic data processing was performed using Room EQ Wizard software. A logarithmic (LOG) sweeps acoustic signal, in a frequency range from 100 to 4000 Hz, was used in the experiment.

To easily compare the acoustic performance of each cement mixture, STL was evaluated in three spectral intervals: low frequency (100–315 Hz), medium frequency (400–2500 Hz) and high frequency (2500–4000 Hz). In each frequency range, the STL value, obtained as an average of four measurements taken on three samples of the same composition, was computed.

2.6 Thermal Characterization: Thermal Conductivity Measurements

Thermal conductivity (TC) tests were performed using a C-Therm TCi thermal analyzer (ASTM D7984) [7] operating following the Modified Transient Plane Source method (MTPS). The measurement system is based on an alumina sensor, a power control device and computer software. A spiral-type heating source is located at the center of the sensor where heat is generated. The sample absorbs some of the heat depending on its TC, and the rest causes a temperature rise at the sensor interface (about 1–3 °C) and a rapid voltage decrease at the heating source. The voltage drop is inversely proportional to the ability of the sample to transfer heat. Thermal conductivity is calculated from the voltage data and the values is provided directly by the software.

Measurements were made at room temperature on previously polished blocks samples, to improve the transmission of the thermal pulse between the specimen and the sensor. For each mixture, four samples were tested. Thermal scanning was performed five times and the TC average values are reported.

3 Results and Discussion

3.1 Printability Test

The printability test made it possible to evaluate the correct rheology of the mixtures, analyze the properties of the hardened material and obtain samples for characterization tests. All mixtures showed good matching of fluidity, extrudability, shape stability and buildability. The printed slabs (Fig. 1), resulting from the deposition process, met the print quality requirements: good surface finish and proper shape retention.

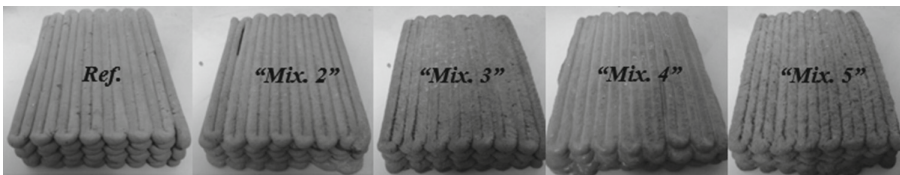


Fig. 1. 3D printed slabs resulting from printability test

3.2 Bulk Density Measurements

As shown in Table 3, the addition of rubber filler affects the bulk density (ρ) cement-based mixes. Increasing the rubber content reduces the unit weight, resulting in lighter cement-based materials. This effect is related to two factors [3, 4]: a) the non-polar nature of rubber filler may tend to entrap air, which in turn increases the air content during the mixing process of the fresh material; b) rubber fillers have lower specific gravity than sand, so the higher the replacement level, the higher the decrease in density.

Table 3. Density of rubber-cement composites as a function of type and rubber weight fraction

Mixture	ρ (Kg/m ³)	% w/w of rubber
Ref.	1927	0%
Mix.2	1641	9%
Mix.3	1340	22%
Mix.4	1624	19%
Mix.5	1468	21%

The most relevant reduction in density (30% reduction) is associated with the mixture containing only RP (*Mix.3*). The fine aggregate has a larger specific surface area, implying a greater tendency to adsorb air in its surface texture.

The cementitious mixtures, developed and investigated in this research, are classified as lightweight concretes. According to European Standard EN 206-1 [8], lightweight concrete is considered to be a cement-based material made with lightweight aggregates resulting in oven-dry density of not less than 800 kg/m³ and not more than 2000 kg/m³.

3.3 Optical Microscopy and Scanning Electron Microscopy (SEM)

The micro-structural OM analysis are shown in Fig. 2.

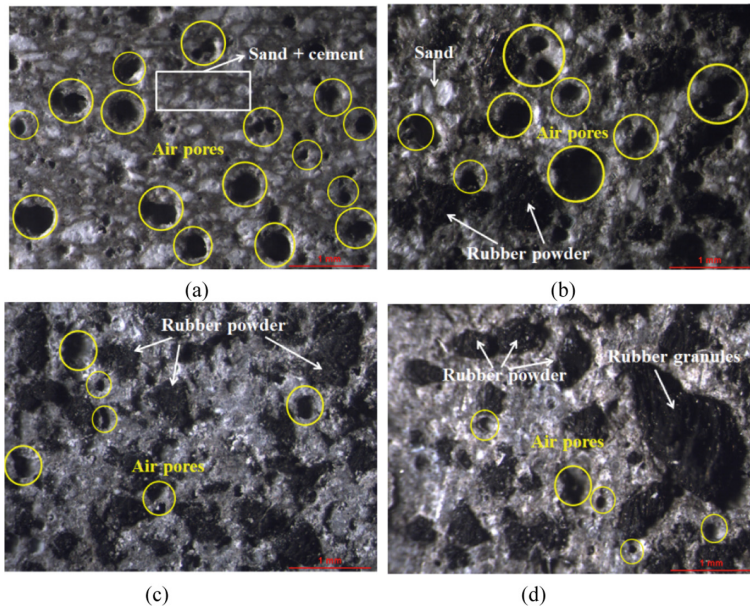


Fig. 2. OM image of the cross-section of the cementitious samples: *Ref.* (a), *Mix.2* (b), *Mix.3* (c) and *Mix.4* (d)

The porosity into a cement-based material is intrinsically associated with the hydration reactions related to the hardening process. The replacement of mineral aggregates with rubber fillers implies a gradual reduction in the entrained air (spheroidal air pores). This effect is due to the lower w/c needed for the production of rubberized mixtures than *Ref. mix* [9].

As shown in Fig. 2d, the most relevant effect occurs in mixtures containing RG (*Mix.4* and *Mix.5*). Coarse TR fillers hinder the micro-cracks propagation in the matrix (“damper” effect) more efficiently than RP and have poor aptitude to adsorb air due to their low specific surface [4].

Besides, SEM micrographs (Fig. 3) show the different interface properties between the rubber fillers and the cement matrix. RG (Fig. 3a) exhibits low adhesion with the matrix and this produces interfacial micro-voids that act like escape spaces for water vapor, resulting in a further reduction in porosity degree. RP (Fig. 3b) provides good adherence with the cement paste and therefore better compaction of mixtures [10].

The lower porosity exhibited by rubberized mixtures is a potentially beneficial aspect of the durability and deformability of the material.

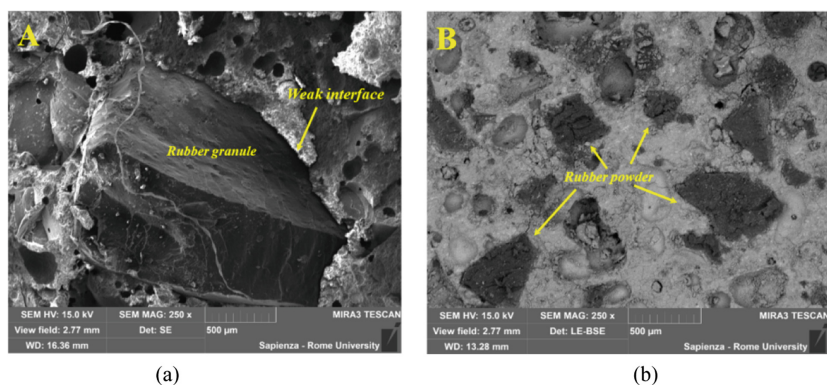


Fig. 3. SEM micrographs of rubber–cement matrix interface: RG (a) and RP (b)

3.4 Mechanical Characterization: Compression and Four-Point Flexural Tests

The flexural and compression tests evaluated the effect of rubber fillers on the mechanical strength, elastic modulus, and elongation at break of the cement-based mixtures. The experimental results are showed in Fig. 4 and Fig. 5.

Elastic module values (orange histogram) depend mainly on the weight percentage of rubber in the mixtures. The cement-based materials, obtained by total replacement of sand with polymeric fillers (*Mix.3*, *Mix.4* and *Mix.5*), show the same reduction in the elastic module as the reference (65% reduction), while *Mix.2* is characterized by a less significant decrease (10% reduction). Cement mixtures can be considered a two-component composite: cement and aggregate. According to the “mixtures rule”, the stiffness will depend on the volumetric fraction and Young’s module of the aggregates

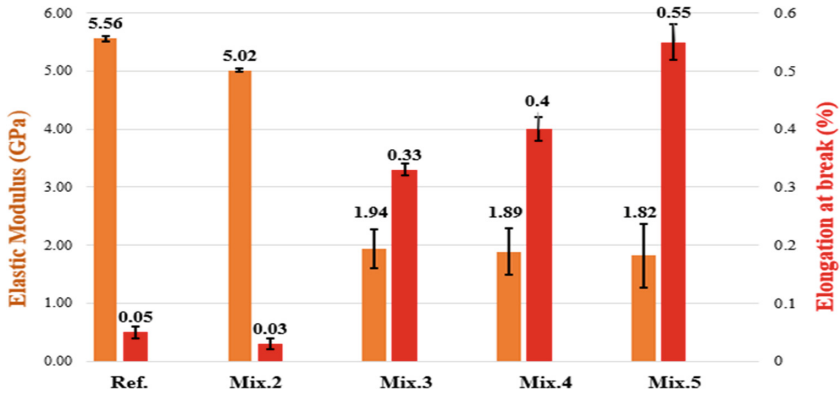


Fig. 4. Mechanical characterization: elastic modulus and elongation at break

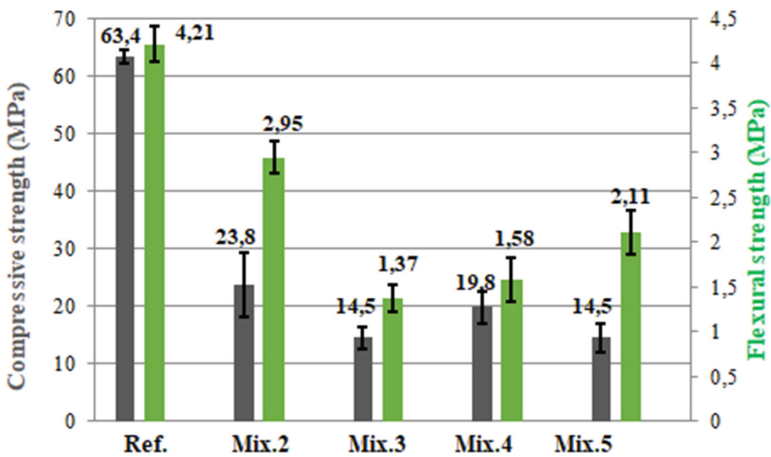


Fig. 5. Mechanical characterization: compression test results

[11]. Replacing the mineral aggregate with TR particles (with less elastic module than sand) increases the deformability of the material, proportional to the amount of polymer aggregate in the mixture. Polymer fillers' morphology influences the ductile behavior of mixtures. The presence of RG (*Mix.4* and *Mix.5*) results in a significant increase in elongation at break (red histogram) to the mixture with only RP (*Mix.3*). The granules more efficiently hinder the initiation and propagation of cracks in the matrix, which affects the greater deformability of the material. *Mix. 2*, containing a part of sand, is stiffer than the other rubberized mixtures.

Figure 5 shows the variation in the compression and flexural strengths to the weight percentage and type of rubber fillers. In general, there is a reduction in the mechanical strength of rubber-based mixtures compared to the *Ref* mix. This trend is related to two factors [12]: a) weak rubber filler-matrix adhesion; b) reduction in material density. According to the experimental data above, the decrease in density is related to the

influence of RP while the poor filler-matrix adhesion is observed in mixtures containing RG. *Mix.4* would appear to show a proper synergy between the two types of fillers, implying a less relevant reduction in compressive strength compared to *Mix.3* and *Mix.5*. It is also possible to observe an increase in flexural strength in the mix with an higher amount of RG. Coarse rubber filler could prevent the cracks propagation and delay the sample failure. The presence of sand in *Mix. 2* results in a higher density than the rubberized mixtures and, therefore better mechanical performances under static load.

According to RILEM indication [13], *Mix.2* and *Mix.4* are categorized as class I structural lightened concretes ($1600 \text{ kg/m}^3 < \text{oven-dry density} < 2000 \text{ kg/m}^3$; compressive strength $> 15 \text{ MPa}$), whose mechanical-physical properties enable to reduce the dead load of structures and improve the sound/thermal insulation performances.

3.5 Acoustic Characterization: STL Measurements

The results from the low, medium, and high frequencies STL tests are shown in Fig. 6. For the low-frequency range, the acoustic behavior of the mixtures is essentially identical (12.3 dB–12.8 dB). Low-frequency acoustic waves are characterized by very long wavelengths that allow it to penetrate easily through the sample. The attenuation of low-frequency waves could be implemented by increasing the thickness of the material [14]. At medium and high frequencies, the effect of polymer fillers on the sound insulation properties of the material is most noticeable. Rubberized mixtures show greater acoustic damping than plain cement-based material. Rubber is a material that can dissipate dynamic energy when vibrating and this property provides better isolation performances. This effect is less significant in *Mix 2*, as the TR amount is lower. Concerning to the filler morphology, the best results obtained for the mixtures with RG, would indicate the influence of the material inertia depending on the size: coarse rubber aggregates, with great inertia, dissipate more energy when vibrated than RP [15]. In the high-frequency range, *Mix.5*, having the largest amount of RG, shows a sound attenuation of 5 dB higher than the *Ref* mix. It can also be seen that despite TR involves low-density mixtures, the insulating properties are better than the plain concrete.

3.6 Thermal Characterization: Thermal Conductivity Measurements

TC is important to understand the thermal insulation of printable rubber-cement composites. Table 4 lists the variation in thermal conductivity with the type of rubberized mixture.

All rubberized mixtures show a decrease in TC compared to the *Ref.* sample. This trend is following the density values: the lower the unit weight of the material the better the thermal insulation properties [4]. The maximum reduction in T.C. values is 67% for *Mix.3* (100% replacement of rubber powder.). As described in Sect. 3.2 paragraph, the fine rubber aggregates cause a greater reduction in density due to their strong tendency to trap air in the material. It is known that the air is a high-performance thermal insulation fluid, so its presence in the mixture hinders the propagation and transmission of thermal energy.

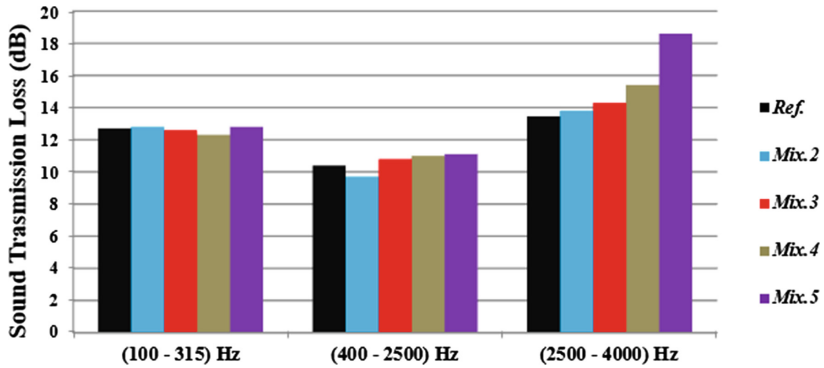


Fig. 6. Experimental STL of rubber-cement mixtures

Table 4. TC of the mixtures

Mixture	ρ (Kg/m ³)	TC (W/mK)	Reduction rate (%)
Ref.	1927	1.32	0
Mix.2	1641	0.78	41
Mix.3	1340	0.43	67
Mix.4	1624	0.84	36
Mix.5	1468	0.81	39

4 Conclusion

In this work, novel printable rubber-cement-mixtures have been developed. The research focused on investigating the effect of recycled TR fillers on the fresh mix printability and the mechanical, thermal, and acoustic performances of the hardened materials. The four rubberized mixtures, with different TR fillers-sand replacement levels, show rheological properties suitable for extrusion-based AM (extrudability, shape retention, buildability). The presence of rubber aggregates implies a reduction in the mechanical strength of the hardened material (due to the reduction in density and the low cement-fillers adhesion) but, thanks to the viscoelastic nature of the polymer aggregates, interesting effects are obtained: reduction in porosity degree, deformability (reduction in Young's module and increasing in elongation at break) and sound and thermal insulation. The combined effect between RP and RG (*Mix.4* and *Mix.5*) results in a beneficial synergy from an engineering point of view: TR fine aggregates maintain good compaction and thermal insulation requirements of the mixture, while coarse fillers act positively on ductility, microstructural features, and acoustic damping behavior.

This study suggests that rubber-cement mixtures are suitable for lightweight applications (blocks, bricks, insulation barriers, pavements). The purpose is to reduce the dead load of the structures, which also results in smaller and lighter elements, reduced construction costs, and promote the sound and thermal requirements.

Thanks to the freedom design characterizing the AM technologies, it is possible to modulate the mechanical and physical properties of the building component by operating on its morphological characteristics, to obtain a “bi-functional” final product. Topological optimization and the study of the potential applications of this material will be the topics of subsequent experimental researches.

Acknowledgements. The authors express their sincere gratitude towards Prof. Valeria Corinaldesi and Eng. Glauco Merlonetti (Marche Polytechnic University) for their support in the additive manufacturing process.

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Properties of Composite Modified with Limestone Powder for 3D Concrete Printing

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Abstract. The design of proper mixes for 3D concrete printing has been already a subject of many studies. Modification to mixes aim to obtain certain properties (extrudability, workability, flowability, open time or buildability) which allow for proper printing of the material. There are different types of reactive or non-reactive mineral additives that were already used to modify the mixes for 3D concrete printing. Studies have already shown the usefulness of fly ash, silica fume, metakaolin, limestone powder or quartz powder. The properties of the mix can also be changed with different chemical admixtures such as plasticizer, accelerators or retarders and viscosity modifying agents. Use of different admixtures can however significantly increase the cost of designed mixes. The study determined the influence of non-reactive limestone powder on the properties of the mix. The mixes were modified with 10% to 50% of additive, that replaced the fine aggregate. Rheological properties of the mixes were studied in this research. The stiffness and load-bearing capacity of mixes ($t \leq 45$ min) were tested. Chosen mixes were printed out to experimentally verify the results. The study has shown that the limestone powder can successfully be used to improve the properties of printing mixes with simultaneous reduction of cement content. The results are promising regarding the sustainable development attitude in modern constructions.

Keywords: 3D concrete printing · Limestone powder · Mix design

1 Introduction

The issues of designing a concrete mix for 3D printing have been on the mind of researchers for a long time [1–7]. The main problem faced by the researchers around the world is to obtain properties such as extrudability, workability, flowability or open time that allows the mix to be used in 3D printing. The parameters are correlated to the rheological properties such as yield point and viscosity. Rheological properties of the

mix correlate also with buildability, which determines how much load can be transferred to printed layer without changes in its shape [2, 8] throughout the whole process of printing. The designed yield point and viscosity must allow the mix to pass through the pumping equipment.

The sustainable development idea requires reduction in consumption of environmentally hazardous materials. One of the key tasks is to reduced the cement consumptions which is responsible for significant amounts of global CO₂ production [9, 10]. Reduction of cement content in the concrete mix results in decreases strength and durability. To obtain necessary rheological and mechanical properties of the mix additional inert or reactive powders such as fly ash, silica fume, metakaolin, limestone powder, quartz powder can be added [4, 5, 7, 10–12]. Changes to the properties can also be imposed by adding chemical admixtures for increased flow rate, accelerators or retarders or viscosity modifying agents [6, 11, 13]. Use of chemical admixtures can however significantly increase the final price of the concrete. The admixtures can improve rheological properties for the mix, but can also drastically change the final properties of the concrete (such as compressive strength). In 3D printing technology utilized for small architecture or low wall elements the strength of the concrete is not the key element. An alternative solution for CO₂ reduction may be the use of geopolymers, which are also made without cement [11, 14–16].

Application of inert microfillers is beneficial in terms of increased viscosity and yield point of the early-age mix. Researchers [17] have added nanoclay and quartz powder to improve the properties of mix. Others have tried to apply the limestone powder to improve the rheological properties [8, 18–20]. Properties of the mixes modified with limestone powder and calcined-clay have also been studied [21].

The aim of the study was to design an alternative mix with reduced cement content with mechanical properties similar to the reference mix (see Sect. 2.1). To modify the properties the authors utilized the inert limestone powder. The study aims to prove that environmentally friendly mixes can be used in 3D printing.

2 Materials and Experimental Procedure

2.1 Research Assumptions

For the purpose of the study a reference mix (B800/LP0) was chosen. The high-performance concrete mix has total of 800 kg/m³ of binder, including fly ash and silica fume. The mix design was a modification of a mix found in [7, 22]. Mix performance and applicability in 3D printing was tested previously [7]. For the purpose of the study 12 mixes were prepared, further described in following chapters. In this study the relationship between axial normal stress and axial normal strain ($(\sigma - \epsilon)$) under compression was tested. The measurements were performed at 15, 30 and 45 min after adding the water. Tests were performed on small cylinder samples ($h = 35$ mm, $d = 60$ mm). The changes in rheological behaviour of the mix was also tested using slump flow table. Chosen mixes were then evaluated by printing a column. For printed samples the buildability, reflected as the stresses at lowest layer were determined. Results of both tests were compared to each other.

2.2 Mix Composition

The twelve mixes were divided in three major groups depending on the content of the binder. The first group included mixes with 800 kg/m^3 of binder, the second 700 kg/m^3 , the last 600 kg/m^3 of binder in the mix. Each group of mixes was modified with 10%, 30% and 50% of limestone powder. The limestone powder was used to replace the fine aggregate. The water/binder ratio was assumed as constant value of 0.3. The binder in each mix consist of 70% of cement, 20% of fly ash and 10% of silica fume. The fly ash used in the study was obtained from a local coal power plant. The notation for the mixes are as follows: B – amount of binder, LP – the amount of limestone powder in the mix. The study assumes a constant slump flow of 135-150 mm at 15 min after adding the water as shown in standard [23]. To obtain assumed slump flow value the mixes were modified with use of superplasticizers. The mix design is presented in Table 1 (the values with * are further described in Sect. 3.1). The reference mix is bolded.

Table 1. Mix design in the study per m^3 .

No	Mix	Binder [kg]	Cement [kg]	Fly ash [kg]	Silica fume [kg]	Percent of limestone powder [%]	Superplasticizer [kg]
1	B800/LP0	800	560	160	80	0%	1.0
2	B800/LP10	800	560	160	80	10%	1.2
3	B800/LP30	800	560	160	80	30%	1.9
4	B800/LP50	800	560	160	80	50%	_*
5	B700/LP0	700	490	140	70	0%	1.6
6	B700/LP10	700	490	140	70	10%	1.9
7	B700/LP30	700	490	140	70	30%	3.3
8	B700/LP50	700	490	140	70	50%	_*
9	B600/LP0	600	420	120	60	0%	2.25
10	B600/LP10	600	420	120	60	10%	2.1
11	B600/LP30	600	420	120	60	30%	_*
12	B600/LP50	600	420	120	60	50%	_*

2.3 Experimental Procedure

The laboratory tests can be divided into six stages:

- 1) Determination of the final mix design for the purpose of early-age mechanical tests. Designed mixes had constant w/b ratio.
- 2) Determination of the slump flow in accordance to [23] at $t_b = 15 \text{ min}$, 30 min and 45 min after adding the water.
- 3) Determination of the relationship between axial normal stress and axial normal strain ($\sigma - \epsilon$) of materials measured in a compression test after 15 , 30 and 45 min

after adding the water. The study was performed on a low-force compression device that allows to impose the force in the range of 5–200 N. The measurement error of the setup is ± 0.5 N. The device has also installed LVDT sensor for displacement measurements. The results of the measurements are registered by a HBM Quantum X at 50 Hz. Specimen after compression test is shown in Fig. 1 a).

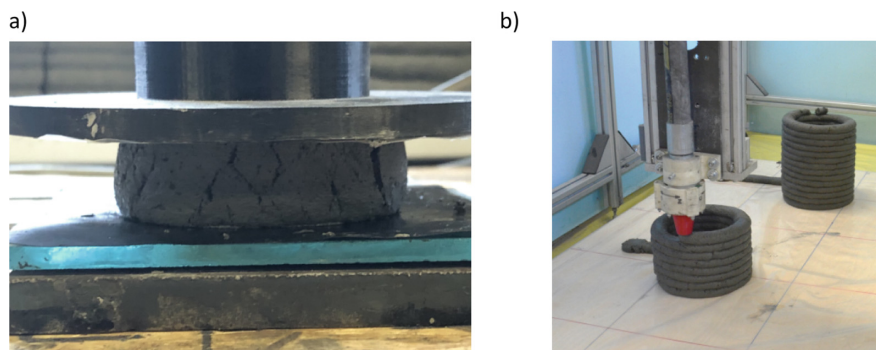


Fig. 1. The testing setup: a) device for mix compression with LVDT sensor, b) 3D printer.

- 4) Determination of compressive strength at 24 h, 72 h and 168 h (7 days) conducted on $4 \times 4 \times 4$ cm samples.
- 5) Choosing the alternative mix with lower amount of binder and similar mechanical parameters as the reference mix (based on the $\sigma(\epsilon)$ correlation) for the purpose of verification in printing test.
- 6) Verification of the assumptions. For the purpose of verification columns with a diameter in axis of 160 mm were designed using G-Code and printed out. Cartesian robot which was using in printing tests is shown in Fig. 1 b). The printing process was continued until the collapse of the structure. The stresses at the lowest layers were determined using formula (1). The verification was performed for the reference mix B800/LP and chosen alternative mix B600/LP10. The quality of printed element were determined according to recommendations found in [5, 7]. The printing process was performed after 15, 30 and 45 min after adding the water. The printing speed was set to $v = 50$ mm/s, which allowed for a whole layer to be printed in ~ 10 s. The concept design and column during printing are presented in Fig. 2.

$$\sigma = h \cdot \gamma \quad (1)$$

$h[\text{m}]$ - height of printed column;

$\gamma[\text{kN}/\text{m}^3]$ – load imposed by the mix.

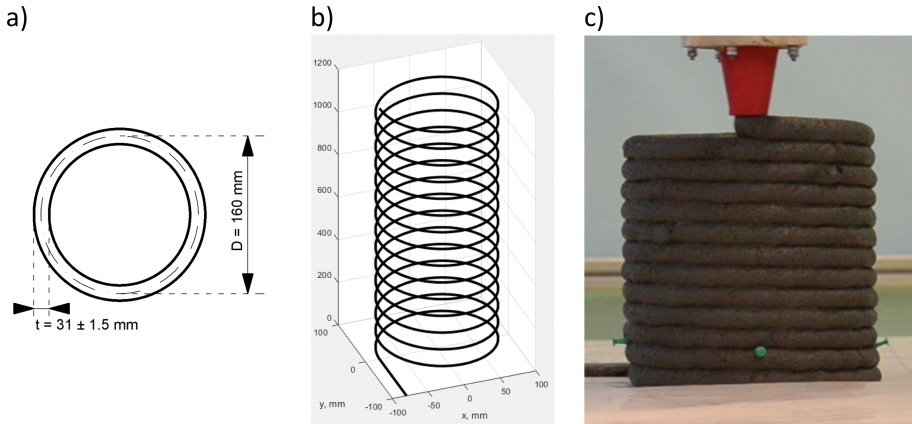


Fig. 2. Verification printed columns: a) cross-section of column; b) path design; c) column during printing.

3 Test Results

3.1 Slump Flow

The initial tests were performed for each mix by determining the amount of super-plasticizer required to reach the assumed slump flow between 135–150 mm. At this stage four mixes (B800/LP50, B700/LP50, B600/LP50 and B600/LP30) were excluded from further considerations as the slump flow could not have been reached without modifying the w/b ratio (* in Table 1).

For chosen mixes the slump flow according to [23] was determined after 15, 30 and 45 min after adding the water. The result are presented in Fig. 3. The results of the tests show similar linear decrease of 13–18 mm for each mix.

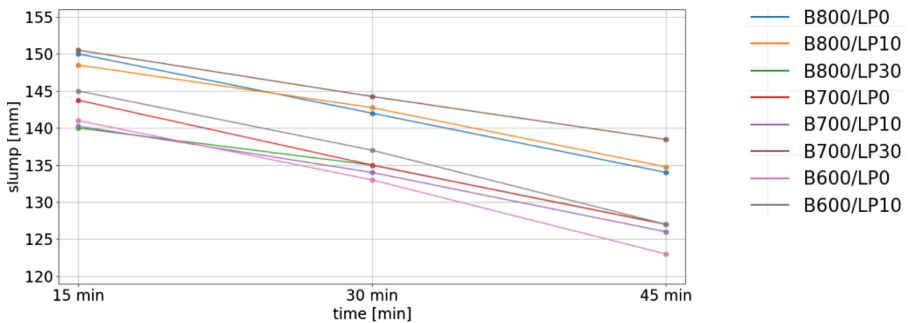


Fig. 3. Slump flow test results.

3.2 Relationship Between Axial Normal Stress and Axial Normal Strain ($\sigma - \epsilon$) Under Compression Test

The results of the $\sigma - \epsilon$ relationship of chosen mixes is presented in Fig. 4 and Fig. 5. Presented results were calculated as a mean from three measurements (CoV between 0.07 and 0.15). It was observed in mixes with high binder content (B800) that the addition of limestone powder significantly increases the mechanical parameters with time (Fig. 4 a)). For mixes with lower binder content (B700 and B600) the increase is insignificant (Fig. 4 b)–d)).

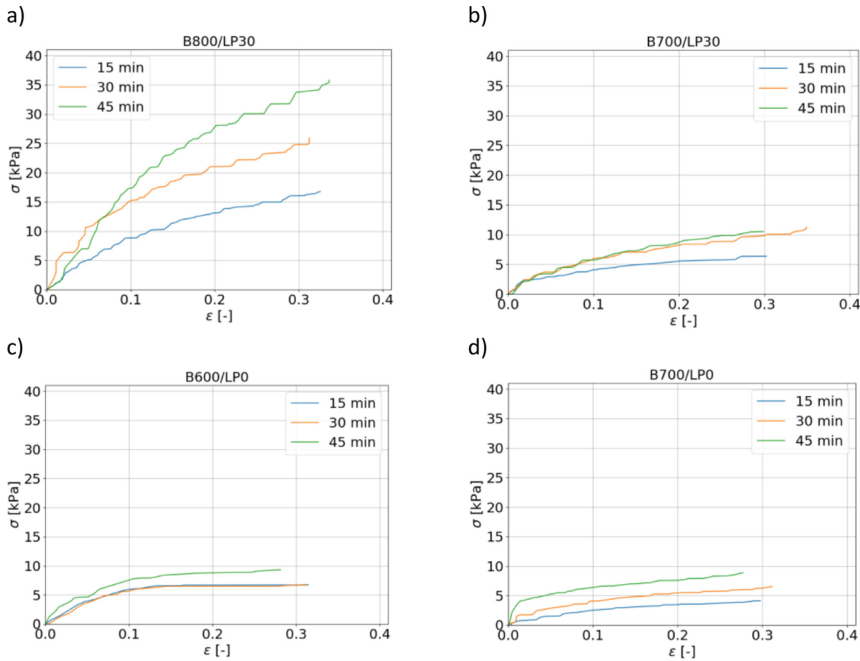


Fig. 4. Relationship $\sigma - \epsilon$ for chosen mixes.

In case of mixes with lower amounts of binder (B700, B600) the addition of limestone powder improved the mechanical properties only after 15 and 30 min (Fig. 5). The differences in the results of B700 and B600 mixes with or without limestone powder are insignificant. Presented graphs show that the limestone powder improves the mechanical properties in each case.

3.3 Compressive Strength

Figure 6 presents the results of compressive strength tests conducted on 4x4x4 cm samples after 1, 3 and 7 days. The highest strength was achieved by the mixes from B800 groups, followed by the B700 and B600 mixes. As expected lower amount of

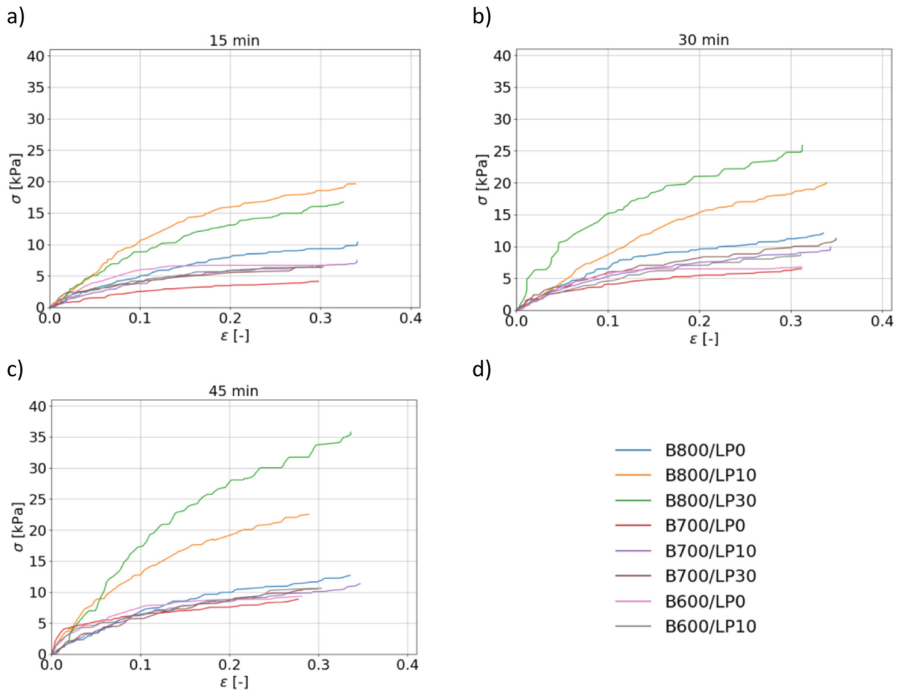


Fig. 5. Development of the $\sigma - \epsilon$ for chosen mixes after 15, 30 and 45 min.

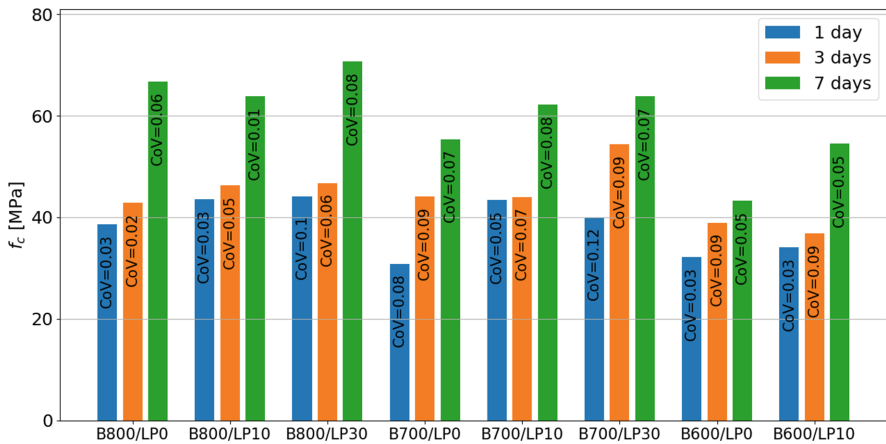


Fig. 6. Compressive strength of studied mixes.

binder in the mix resulted in lower compressive strength. In B800 groups, replacement of the fine aggregate with limestone powder did not improve the mechanical parameters. The existence of the limestone powder in the B700 and B600 mixes improves the compressive strength.

3.4 Verification by Printing Test

As an alternative mix the authors chose the B600/LP10 mix which exhibited similar characteristics as the reference mix B800/LP0 [7]. The choice was made based on the development of $\sigma - \epsilon$ relationship. As the results were similar in case of every mix, the choice was also made considering the lowest amounts of binder with simultaneous high compressive strength. It is worth mentioning that mixes B800/LP10 and B800/LP30 had better mechanical characteristics than the reference mix. They were however excluded from further consideration due to their high amount of binder.

The verification was performed as described in the Sect. 2.3. Each test was performed three times. The columns were printed for both chosen mixes (B800/LP0 and B600/LP10). The columns were printed only 15 and 30 min after adding the water. After 45 min the open time of the mixes was close to the limit which caused them to be impossible to use for printing. Figure 7b) presents the B600/LP10 mix column when the bottom layer's strength was exceeded (during collapse). Figure 7a) presents the comparison of results for small cylindrical samples and printed column models. The study has proven that there is a qualitative and quantitative relationship between smaller samples and printed column models. In each studied case the small samples had higher strength than the printed elements. The result is probably caused by the fact that the smaller samples had to be compacted for the test. The mix during pumping is not compacted properly causing in decrease of strength. The strength ratio of small cylindrical samples to printed column samples was between 1.61–1.72. The strength of columns printed with the alternative mix was slightly higher than for the reference mix. Similar results were obtained in the smaller samples test.

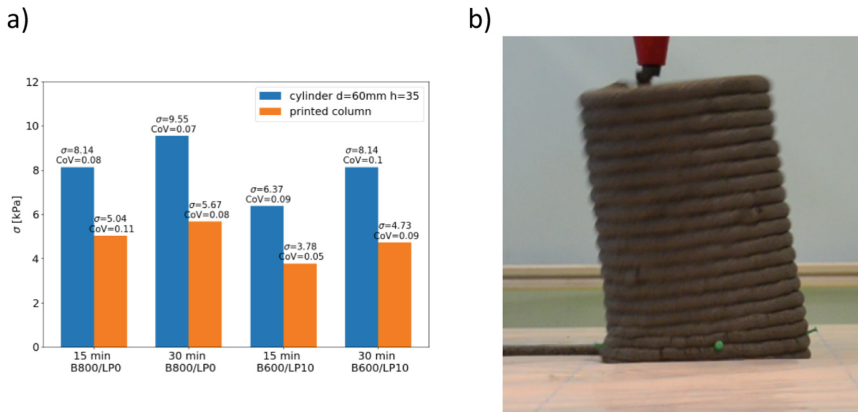


Fig. 7. a) Comparison of results of small samples and columns, b) column collapse during the test.

The verification tests proved that for mixes with lower cement content, the modification with limestone powder can help to obtain required properties for 3D printing.

4 Conclusion

Performed tests proved that the addition of limestone powder without modification to the overall binder content can improve the buildability of the mixes. The higher the amounts of limestone powder better the 3D printing rheological parameters. The higher the initial binder content greater the influence of the limestone powder on the rheological properties. For higher binder content mixes, the addition of the limestone powder did not influence the compressive strength of concretes. On the contrary, limestone powder seems to improve the compressive strength when the amount of binder is lower.

It was proven that modification of the concrete mix with limestone powder, even for mixes with lower binder content allowed to obtain similar buildability as in reference mix, which had much higher binder content. This was both proven for smaller samples (Sects. 3.2 and 3.4) and printed columns (Sect. 3.5). This shows the usefulness of limestone powder in 3D printing, not only regarding its impact on the rheological parameters, but due to possible reduction in cement usage, which is one of the key elements of sustainable development.

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23. EN 1015-3:2000. Methods of test for mortar for masonry - part 3: determination of consistence of fresh mortar (by flow table)



Effect of Limestone Powder Substitution on Fresh and Hardened Properties of 3D Printable Mortar

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Abstract. Great progress has been made in 3D concrete printing (3DCP) in the past few years. The unique advantages of 3DCP over conventional concrete construction may include saving costs and labor, eliminating formwork, reducing the construction time, as well as increasing flexibility in architectural design. To satisfy the printing requirements, a high amount of binders is used for 3DCP. Among all the binders, ordinary Portland cement (OPC) is the most commonly used binder for 3DCP. However, producing OPC consumes high amounts of energy and exhausts high amounts of greenhouse gases. Therefore, with a high amount of OPC, 3DCP cannot be treated as a sustainable and environmental friendly construction method. Partially replacing OPC by supplementary cementitious materials (SCMs) might be a proper solution to make the 3D printable concrete sustainable. Limestone powder (LP) is one of the SCMs with the advantage of wide availability and low cost. This study analyzed the impact of substituting OPC by LP on the fresh and hardened properties of 3D printable mortar. Six mixtures with three LP substitution rates (0%, 25%, and 50% by volume of OPC) were designed. In the fresh stage, a squeeze flow test was used for evaluating the shape stability. In the hardened stage, drying shrinkage and mechanical properties were investigated. The results showed that a high amount of LP substitution had negative effects on both fresh properties and hardened properties. However, for a lower replacement percentage (i.e. a 25% replacement rate), the strength loss is still within reasonable limits.

Keywords: 3D printing · Limestone powder · Shape stability · Drying shrinkage · Mechanical behavior

1 Introduction

3D concrete printing (3DCP) technology broadens the horizons and brings new opportunities to concrete construction industries [1]. The possibility to build concrete structures without formwork is a major advantage in view of the reduced costs, improved fabrication rates, higher architectural freedom, and safer construction environments [2, 3].

However, to satisfy the required fresh properties of 3D printable concrete, a high binder content was used. Among all the binders, ordinary Portland cement (OPC) accounts for a large proportion (more than 70%) of the binders used for 3DCP [4]. Unfortunately, producing OPC is an energy consuming process and a polluting process. With regard to the high consumption of OPC, 3DCP cannot be regarded as a sustainable construction method compared to conventional construction methods. Partially replacing OPC by supplementary cementitious materials (SCMs) might be a proper solution.

Many researchers started to look for suitable SCMs to decrease the use of OPC in 3D printable concrete. A mix design proposed by Nerella et al. [5] contained 55% of OPC, 30% of fly ash, and 15% of silica fume as binder. The strategy of using a high volume of fly ash or slag substitution in 3DCP was developed by Panda et al. [6]. However, the main problem for silica fume and slag is the limited quantity of their availability worldwide [7]. The amount of available fly ash is higher, however, more than 66% of available fly ash is not suitable for blending with cement due to quality reasons [8]. Limestone powder (LP) is one of the SCMs with the advantage of wide availability and low cost [9, 10]. A large amount of limestone was utilized by Bentz et al. [11] to develop a sustainable cementitious binder for extrusion based 3D printing.

This study analyzed the impact of substituting OPC by LP on the fresh and hardened properties of 3D printable mortar. Six mixtures with three LP substitution rates (0%, 25%, and 50% by volume of OPC) were formulated. The results of a squeeze flow test showed that LP substitution had an obviously negative effect on the shape stability. In the hardened stage, a higher substitution of OPC by LP increased the drying shrinkage. In addition, OPC replacement by LP decreased the compressive strength and flexural strength of 3D printable mortar. However, for mixtures with only a 25% substitution rate, a qualified strength which was higher than 30 MPa was obtained.

2 Experimental Program

2.1 Materials

The main materials used in this study were OPC, obtained from Holcim and LP, obtained from Carmeuse. The chemical compositions of OPC and LP are given in Table 1. Sand with a maximum particle size of 2 mm was used. The sieve curves of OPC, LP and sand are shown in Fig. 1. The density of the used OPC, LP and sand was 3170 kg/m³, 2710 kg/m³ and 2650 kg/m³, respectively.

Table 1. Chemical composition and loss on ignition (LOI) of OPC and LP.

(%)	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃	Cl ⁻	LOI
OPC	64.3	18.3	5.2	4.0	1.4	0.32	0.43	3.5	0.06	2.7
LP	48.85	8.15	1.28	0.88	1.41	1.25	0.28	0.05	–	37.29

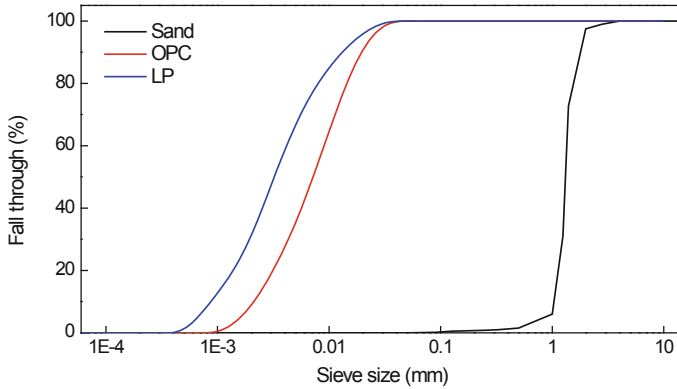


Fig. 1. Sieve curves of OPC, LP and sand.

Liquid polycarboxylate ether (MasterGlenium 51 obtained from BASF) was used as superplasticizer (SP). Powdery hydroxypropyl methyl cellulose (MOT 60,000 YP4 obtained from Shin-Etsu) was used as the viscosity modifying admixture (VMA). Anhydrous sodium carbonate powder was used as the flash setting admixture (FSA).

Mixtures with two sand to binder ratios (1.79 and 1.39 by volume) and three LP substitution rates (0%, 25%, and 50% by volume) are shown in Table 2. The dosages of SP, VMA, and FSA were kept constant in all mixtures.

Table 2. Composition of the mixtures (kg/m³).

Composition	Sand	OPC	LP	Water	SP	VMA	FSA
S1-LP0	1048.2	698.8	0	244.6	3.5	1.4	3.5
S1-LP25	1048.2	524.1	149.3	244.6	3.5	1.4	3.5
S1-LP50	1048.2	349.4	298.7	244.6	3.5	1.4	3.5
S2-LP0	922.8	790.9	0	276.8	4.0	1.6	4.0
S2-LP25	922.8	593.2	169.0	276.8	4.0	1.6	4.0
S2-LP50	922.8	395.5	338.0	276.8	4.0	1.6	4.0

The batches were prepared in a conventional planetary mixer according to the following protocol: (1) manual mixing of SP with water; (2) mixing dry powders (OPC, LP, VMA and FSA) at 140 rpm for 10 s; (3) adding water (and SP) to pre-mixed powders; (4) mixing the paddle at 140 rpm for 30 s; (5) adding the sand and mixing the paddle at 140 rpm for 30 s; (6) mixing the paddle at 285 rpm for 30 s; (7) scraping and resting for 90 s; (8) mixing the paddle at 285 rpm for 60 s.

2.2 Methods

Within this study, the previously mentioned mortars were investigated in the fresh and the hardened stage. In the fresh stage, the shape stability was investigated by a squeeze

flow test. In the hardened stage, the evolution of drying shrinkage with time was measured under controlled temperature and humidity conditions. In addition, the compressive strength and the flexural strength was also determined to better characterize the material and better evaluate its behavior.

First, the squeeze flow test was performed on an Anton Paar MCR rheometer with a parallel-plate geometry, as shown in Fig. 2. The top and bottom plates were smooth steel plates with a diameter of 50 mm. A plastic circular mold was used for casting the samples. The inner diameter of the mold measured also 50 mm. The height of the mold was 10 mm, the same as that of one commonly printed layer. The samples were cast in the plastic circular mold and demolded immediately. The loading rate applied on the samples amounted to 0.04 N/s. The samples were tested 30 min after mixing water and binders. The corresponding load-displacement curves were obtained.

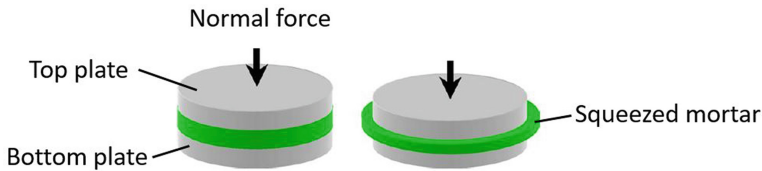


Fig. 2. Schematic diagram of the squeeze flow test.

After evaluating the shape stability, three prismatic specimens ($40 \times 40 \times 160 \text{ mm}^3$) were molded and compacted by vibration to measure the drying shrinkage. In the first 24 h, the specimens were covered with aluminum foil. After 24 h, the specimens were demolded and subjected to a controlled environment ($T = 20^\circ\text{C}$, $\text{R.H} = 65\%$) for 27 days. On the surface of each specimen, two DEMEC points were fixed with a gauge length of 150 mm. The drying shrinkage was measured by every day during the first week and every two days afterwards.

For each mix composition, six more prismatic specimens ($40 \times 40 \times 160 \text{ mm}^3$) were molded and cured in a controlled environment ($T = 20^\circ\text{C}$, $\text{R.H} = 65\%$) for evaluating the compressive strength and flexural strength. Three specimens were tested at the age of 3 days and three other specimens were tested at the age of 28 days. In addition, the density of the hardened samples was measured at the age of 28 days.

3 Results and Discussion

3.1 Shape Stability

As there is no support of formwork, shape stability is an important requirement for printable mixtures. Therefore, it is necessary to evaluate the shape stability of a new developed mixture. Figure 3 shows the normal force versus displacement curves that were recorded in the squeeze flow test.

It was shown that for the same loading protocol, the displacement of different mixtures was quite distinct. Comparing mixtures S1-LP0, S1-LP25 and S1-LP50 in the

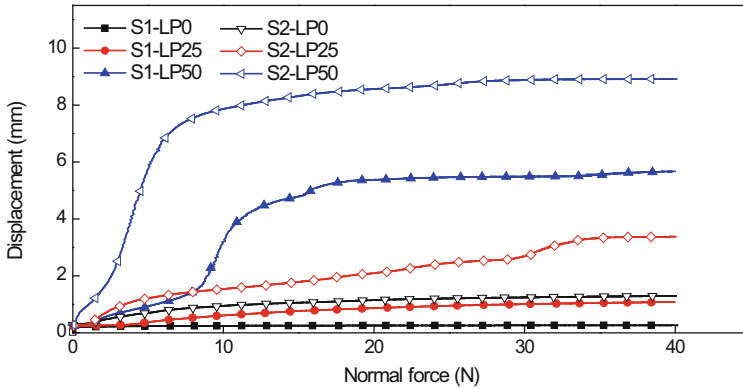


Fig. 3. Normal force versus displacement curves.

S1 series (or S2-LP0, S2-LP25 and S2-LP50 in the S2 series), it was obvious that the shape stability decreased with the increase of LP substitution, indicating a higher risk facing collapse during the 3D printing process. Therefore, either the construction height or the printing speed would be restricted in the case of substituting OPC by LP. In addition, it was shown that in the case of the same substitution of OPC by LP, the mixture with a higher sand to binder ratio (S1 series) presented a stronger shape stability (i.e. a smaller displacement).

With regard to the elastic-plastic behavior, the plastic stage was not obvious in the case of 0% and 25% substitution of OPC by LP (i.e. mixture S1-LP0, S1-LP25, S2-LP0 and S2-LP25). While in the case of 50% substitution of OPC by LP (i.e. mixture S1-LP50 and S2-LP50), an obvious plastic stage where the materials deformed considerably while the normal force barely increased was observed.

Previous studies have proven that the effect of LP on the workability of concrete could be mainly attributed to the morphological effect, filler effect, and dilution effect [12]. In previous studies, inconsistent morphologies of LP were reported. Some scholars [13] observed a rough surface morphology. However, others [14] observed a spherical morphology. Since SEM analysis of the LP used in this study has not yet been finished, the morphological effect will not be discussed. Because the particle size of LP used in this study was similar to that of OPC, negative effects of LP on the shape stability of 3D printable mortar could be mainly attributed to the dilution effect. With the substitution of OPC by LP, the OPC content was reduced. Moreover, fewer ions would release inside the 3D printable mortar. As a result, the electrostatic interaction between cement particles decreased, leading to the reduced shape stability. Therefore, other approaches (e.g. reducing water amount, or increasing FSA dosage) should be taken to make up for a loss in shape stability in the case of substituting OPC by LP.

3.2 Drying Shrinkage

3D printed structures are exposed to drying shrinkage immediately after the fabrication process. Therefore, moisture escapes from the surface of printed layers, which will

result in drying shrinkage. Figure 4 and Fig. 5 show the evolution of the drying shrinkage of the two series of 3D printable mortar (S1 series and S2 series). The results clearly show the same trend of drying shrinkage for all curves, which was much higher in the first several days. The results were consistent with previous studies [15]. In the case of S1 series, the average drying shrinkages of mixtures with 25% and 50% LP substitution were 104.8% and 113.9%, respectively, of the final shrinkage of reference mixture (S1-LP0) after 28 days. With regard to S2 series, the final drying shrinkage of mixtures with 25% and 50% LP substitution were 115.2% and 126.6%, respectively.

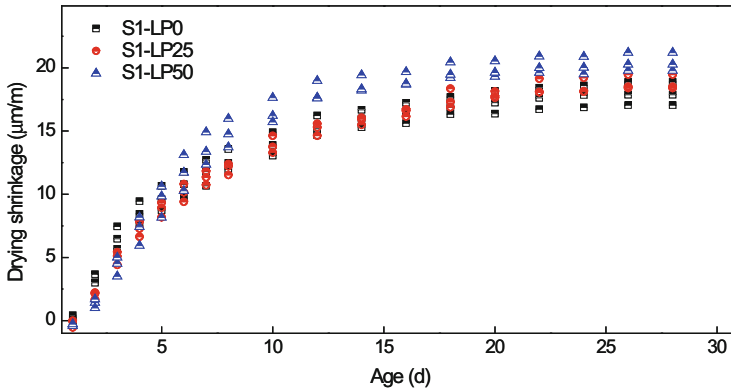


Fig. 4. Drying shrinkage of the tested samples (S1 series).

Because all of the mixtures contained a similar volume of paste, the OPC content in the paste was the most influential parameter on the drying shrinkage, which was also observed in previous studies [16]. With the substitution of OPC by LP, the water to cement ratio increased, leading to a higher quantity of available capillary water that would be lost by drying. As a result, an increased drying shrinkage was observed with the increase of LP substitution rate.

3.3 Mechanical Properties

Compressive strength and flexural strength test results at 3 days and 28 days are given in Fig. 6 and Fig. 7, respectively.

It can be easily seen that, regardless of curing age, there was a decrease in the compressive strength with the increase of LP substitution rate. Moreover, for 28 days, compared to the reference mixture (S1-LP0), decreases were 27.5% and 66.1% respectively for the replacement of 25% and 50% OPC by LP for S1 series. With regard to S2 series, decreases in compressive strength for the replacement of 25% and 50% OPC were 15.6% and 66.7%, respectively. This decrease in the compressive strength was related to a dilution effect that reduced the hydration of OPC. OPC, which resulted in a higher amount of hydration products, was one of the most important, even superior, parameters that effected compressive strength values. An enhancement in hydration rate was reported when LP substitution rates lower than 15% were used [12].

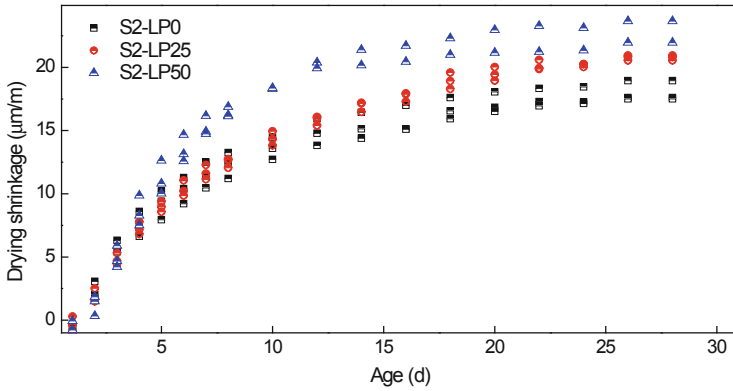


Fig. 5. Drying shrinkage of the tested samples (S2 series).

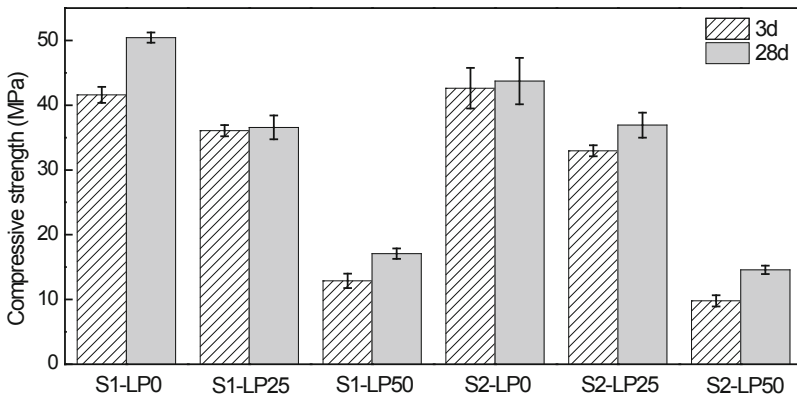


Fig. 6. Compressive strength of the tested samples.

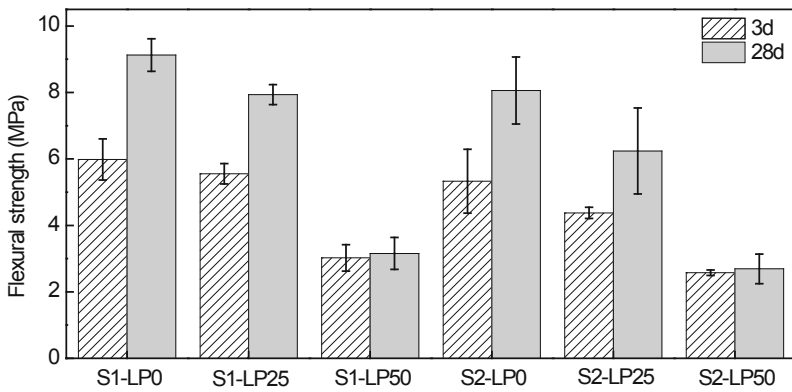


Fig. 7. Flexural strength of the tested samples.

When this level was exceeded, and the amount of OPC was further reduced, a decrease in compressive strength was observed [12]. However, it was still possible to notice that mixtures with 25% LP substitution (S1-LP25 and S2-LP25) achieved compressive strengths above 30 MPa which is still sufficient for applications in 3DCP.

Figure 6 indicates that the substitution of OPC by LP did not improve the flexural strength. For 28 days, compared to the control mixture S1-LP0, 13.0% and 65.4% decreases were observed for replacement levels of 25% (S1-LP25) and 50% (S1-LP50). In the case of S2 series, the same trend with decreases of 22.6% and 66.6% was observed.

Flexural strength is mainly attributed to the binder rather than the presence of other ingredients [17]. The increase in the substitution rate of LP resulted in a lower amount of hydration products and this mainly led to a higher porosity and a weaker interfacial transition zone [18]. All these resulted in a decrease in flexural strength, as shown in Fig. 6.

In addition, the average density of samples after 28 days was measured and listed in Table 3. It was obvious that the substitution rate of LP had a significant effect on the density of hardened samples. Comparing to the reference mixture S1-LP0, the density of S1-LP25 and S1-LP50 dropped 7.4% and 27.0%, respectively. For S2 series, the decreases amounted to 6.5% and 29.9% for the LP replacement level of 25% and 50%.

Table 3. Average density after 28 days (kg/m³).

Mixtures	S1-LP0	S1-LP25	S1-LP50	S2-LP0	S2-LP25	S2-LP50
Density	2069.02	1916.86	1510.17	1982.94	1853.13	1390.66

4 Conclusions

It is possible to reduce greenhouse gas emissions substantially with the use of high-volume LP instead of OPC in 3DCP. This study investigated the influence of LP substitution on the fresh and hardened properties of 3D printable mortar. The following conclusions were reached:

- (1) Negative effects of LP on the shape stability of 3D printable mortar could be mainly attributed to the dilution effect. With the substitution of OPC by LP, the cement content was decreased, leading to a weaker electrostatic interaction between cement particles. Increasing FSA dosage might be useful to enhance the shape stability.
- (2) With the increase of LP substitution rate, drying shrinkage increased. Because the increased water to cement ratio resulted in a higher quantity of available capillary water that would be lost by drying.
- (3) Increase in LP substitution rate did not improve compressive strength and flexural strength. Fortunately, with a limited range of LP substitution, the mechanical properties still met the requirements.

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Rheology Evaluation of Cement Paste with Nanoclays, Nanosilica and Polymeric Admixtures for Digital Fabrication

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Abstract. Additive and digital manufacturing have opened wide new opportunities in architectonic design with cement based materials. However, there are still some issues to be addressed regarding rheological properties' control. Among rheology modifiers, nanoclays, nanosilica and polymeric admixtures can be used to adjust rheological properties of cement paste, as yield stress, viscosity and thixotropy. These rheological properties are a key factor to control technological requirements as pumpability, extrudability and buildability. An experimental study was carried out to evaluate the combined effects of nanoclays, nanosilica and polymeric admixtures on cement paste rheology for digital fabrication, considering their interactions and synergies. A reference paste with ordinary Portland cement blended with limestone filler, 2:1 by cement weight, and a low water to binder ratio was designed. Then, four different nanoclays - attapulgite, bentonite and two types of sepiolite-, a commercial nanosilica, two types of viscosity modifying admixtures (VMA) and a high range water reducing admixture (HRWRA) were added. Flowability of cement pastes was assessed with the minicone slump test and the synergetic effect and interactions between nanoclays, nanosilica and polymeric admixtures were evaluated.

Keywords: Nanoclays · Nanosilica · Polymeric admixtures · Rheology · Digital fabrication

1 Introduction

Digital fabrication has opened wide opportunities to freeform architecture design and precision material placement with cement based material. Among digital fabrication techniques, additive fabrication has many advantages in this field as fast construction speed, efficient structural design, reduced cost labor and framework, etc. [1]. However, this technology has many challenges to be addressed regarding its technological requirements to achieve optimal pumpability, extrudability and buildability [2, 3]. Rheology parameters of cement based materials have been identified to be essential for controlling the technological requirements of digital fabrication [4].

Several digital technologies have been developed for architectural applications as layered extrusion, binder jetting and slip-forming [1, 2]. All of them need to control rheological properties to place the material. Besides, these rheological properties have

to change over time in order to fulfill all the technological requirements [5]. Pumpability requires low yield stress and viscosity. On contrary, extrudability and buildability require a high yield stress and viscosity parameters. Thixotropy is related to the change over time of these rheological parameters. And adjusting thixotropy becomes a key factor to success on digital fabrication with cement based materials [5]. Mini-cone Slump test has demonstrated to be a useful field-oriented test to evaluate rheology of cement paste [6, 7].

The use of Nanotechnology is a promising way to adjust cement paste rheology. Among nanocomponents that can be used for this purpose, Nanoclays (*NC*) are able to increase static yield stress and viscosity, without change dynamic yield stress [8–10]. Hence, *NC* can improve buildability and shape stability without detriment on pumpability [11]. Moreover, silica based components can increase yield stress and cohesiveness of fresh cement paste, enhancing shape-stability [11–13]. On the other hand, polymeric admixtures have also been used to modify rheology parameters. High range water reducing admixtures (HRWRA) has been added on cement paste to improved pumpability reducing yield stress [9, 14, 15]. Besides, other polymeric admixtures as viscosity modified admixtures (VMA) have been used to increase viscosity and thixotropy of pastes [12, 13, 16–18].

The use of *NC* and nanosilica (*NS*) jointly with polymeric admixtures is a promising opportunity to modify rheology of cement paste. Their synergetic effect on cement paste could speed up yield stress and viscosity growth, improving its structural build-up capacity (effective thixotropy) [2, 5, 12, 19]. Thus, the technological requirements of digital fabrication can be achieved from the material composition design.

In this study, a rheology characterization using the mini-cone slump test of cement paste blended with limestone filler, four different *NC*, *NS* and three polymeric admixtures was carried out. The aim of this study was to evaluate the combined effects of *NC*, *NS* and polymeric admixtures synergies on cement paste rheology in order to design practical mixtures to digital fabrication.

2 Experimental Program

2.1 Material Compositions

The cement/limestone filler paste used in this study are summarized in Table 1. A reference paste containing a CEM I 42.5R cement blended with limestone filler (2:1 by cement weight), water to binder ratio (w/b) of 0.35 was designed. Then, a colloidal nanosilica (*NS*) and four different nanoclays (*NC*) were included: Attapulgite (*Att*), Bentonite (*Be*) and two sepiolites, one in powder form (*Sep*) and other dispersed in water (*Sew*), all of them 2% by cement weight. Further information of these components has been previously published [8].

Additionally, three polymeric admixtures were added: a high range water reducing admixture in polycarboxylate ether based (HRWRA), a poly(acrylamide-co-acrylate)-based viscosity modified agent (VMA1) and a polyether-methylcellulose-based viscosity modified agent (VMA2). VMA1 was added in 0.2% and VMA2 was added in

Table 1. Compositions of cement pastes under study (components in g)

	CEMI 42,5R	Lim. Filler	Water	w/b	VMA1	VMA2	NC	HRWRA
REF	850	425	446	0.35	–	–	–	0–2.5% *b
ATT	850	425	446	0.35	–	–	17	
BE	850	425	446	0.35	–	–	17	
SEP	850	425	446	0.35	–	–	17	
SEW	850	425	386*a	0.35	–	–	77.2*c	
NS	850	425	386*a	0.35	–	–	77.2*c	
VMA1- 02ATT	850	425	446	0.35	1.7	–	17	
VMA2- 02ATT	850	425	446	0.35	–	1.7	17	
VMA2- 04ATT	850	425	446	0.35	–	3.4	17	
VMA1- 02BE	850	425	446	0.35	1.7	–	17	
VMA2- 02BE	850	425	446	0.35	–	1.7	17	
VMA2- 04BE	850	425	446	0.35	–	3.4	17	
VMA1- 02SEP	850	425	446	0.35	1.7	–	17	
VMA2- 02SEP	850	425	446	0.35	–	1.7	17	
VMA2- 04SEP	850	425	446	0.35	–	3.4	17	
VMA1- 02SEW	850	425	386 *a	0.35	1.7	–	77.2*c	
VMA2- 02SEW	850	425	386 *a	0.35	–	1.7	77.2*c	
VMA2- 04SEW	850	425	386 *a	0.35	–	3.4	77.2*c	
VMA1- 02NS	850	425	386 *a	0.35	1.7	–	77.2*c	
VMA2- 02NS	850	425	386 *a	0.35	–	1.7	77.2*c	
VMA2- 04NS	850	425	386 *a	0.35	–	3.4	77.2*c	

*a Liquid water added.

*b HRWRA was employed as an increment dosage scale, by cement weight.

*c water of the components (SEW and NS) was also taken into account. Sew and Ns solid residue was 22%.

two amount 0.2 and 0.4%, all by cement weight. To reach the required fluidity, HRWRA was used in a ranging between 0 to 2.5%, by cement weight [16].

2.2 Experimental Methods

Mini-cone slump test was used to evaluate fresh cement paste flowability. A mini-cone with dimension $100 \times 70 \times 50$ mm (upper diameter - lower diameter - height, respectively) was filled and lifted up. Then, paste started to spread until reaching final spread diameter, final height and final spread time. The paste spread was recorded with a webcam and the flow parameters were measured. Besides, a lateral picture of final height was taken. The measured parameters in this test can be correlated with rheological parameters of cement paste as, yield stress and viscosity. According to literature, final spread diameter can be correlated to yield stress and final spread time with viscosity [6, 7].

3 Experimental Results

Figure 1 presents final spread diameter with different percentages of HRWRA results obtained with mini-cone slump test on pastes with nanoclays (*NC*), nanosilica (*NS*) and polymeric admixtures.

Figure 1a shows the effects of *NC* and *NS* on flowability of pastes without polymeric admixtures. Pastes with *NC* and *NS* showed 3 different behaviors. Reference, *Att* and *NS* pastes required a low amount of HRWRA to spread. Both sepiolites (*Sep* and *Sew*) required twice amount of HRWRA than *Att*. Finally, Bentonite (*Be*) needed three times of HRWRA amount to spread [8].

Figure 1b presents pastes with *NC*, *NS* and VMA1. These results showed a similar behavior than results without VMA1, although all the pastes required a higher amount of HRWRA to reach similar values of final diameter. All *NC* and *NS* required 0.2 or 0.4% of HRWRA more than its references without VMA1. Besides, *Sep* with VMA1 needed a slight high amount of HRWRA than *Sew*.

Figure 1c and d plots pastes with *NC*, *NS* and VMA2 in two amounts 0.2 and 0.4%. *Att* and *NS* did not present any differences regarding the reference and its samples without VMA2. However, *Be* showed a major change with the addition of VMA2. *Be* with VMA2 required the same amount of HRWRA than *Att* and *NS*, whereas *Be* without VMA2 required three times this amount of HRWRA (Fig. 1a). Sepiolites with 0.2% of VMA2 (Fig. 1c) did not showed changes regarding to their references (Fig. 1a). Nevertheless with 0.4% of VMA2 (Fig. 1d), *Sew* required a slight higher amount of HRWRA than *Sep* in contrast to sepiolites with VMA1 (Fig. 1b).

Figure 2 plots the final spread times of pastes with *NC*, *NS* and polymeric admixtures with different % of HRWRA measured with mini-cone slump test.

Figure 2a shows the final spread times of pastes with *NC* and *NS* and without VMA. These results agree with those measured for spread diameters described previously (Fig. 1a), showing three behaviors. Although, *NS* showed final times similar to sepiolites. *Att* was the nanoclay with longer final time values and lower amount of HRWRA was required. On the contrary, *Be* showed shorter final time values and demanded larger amounts of HRWRA.

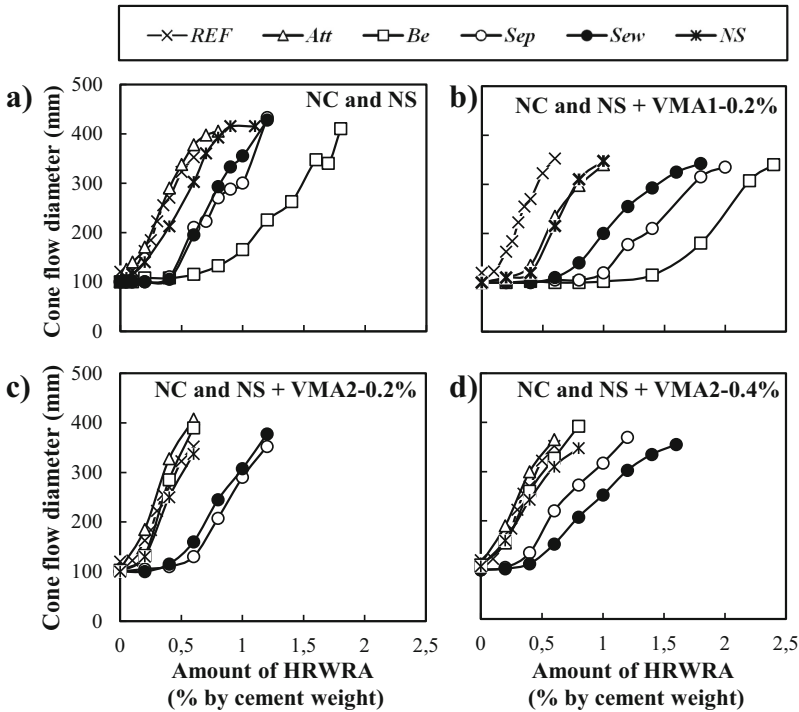


Fig. 1. Final diameter results of mini-cone slump test. (a) Final diameter vs % HRWRA of pastes with NC and NS; (b) Final diameter vs % HRWRA of pastes with NC, NS and VMA1; (c) Final diameter vs % HRWRA of pastes with NC, NS and 0.2% of VMA2; (d) Final diameter vs HRWRA% of pastes with NC, NS and 0.4% of VMA2.

Figure 2b presents the final time results of pastes with NC, NS and VMA1. All pastes showed an increase of final time values regarding to pastes without VMA1. *Att* showed the highest final time values. Sepiolites and NS presented similar final time values but NS needed less HRWRA than both sepiolites. *Be* increased final time values regarding to its reference paste, although it showed the lowest values among all NC with VMA1.

Figure 2c and d plot final time results of pastes with NC and 0.2 and 0.4% of VMA2. *Att* and NS showed higher final time values than references (Fig. 2a), although the amount of VMA2 did not seemed to affect this value. *Be* with 0.2% of VMA presented almost the same value as reference. However, *Be* with 0.4% was the nanoclay with longer final time value. Although, notably less amount of HRWRA was required by *Be* with VMA2. Moreover, both Sepiolites with 0.2% of VMA2 showed similar final times to references while sepiolites with 0.4% of VMA2 showed higher values. Hence, VMA2 at 0.4% was able to increase final time values regardless the amount of HRWRA and the nanoclay type.

In addition, mini-cone results were used to calculate yield stress and viscosity rheological parameters for pastes with 0.2% and 0.6% of HRWRA. Yield stress was

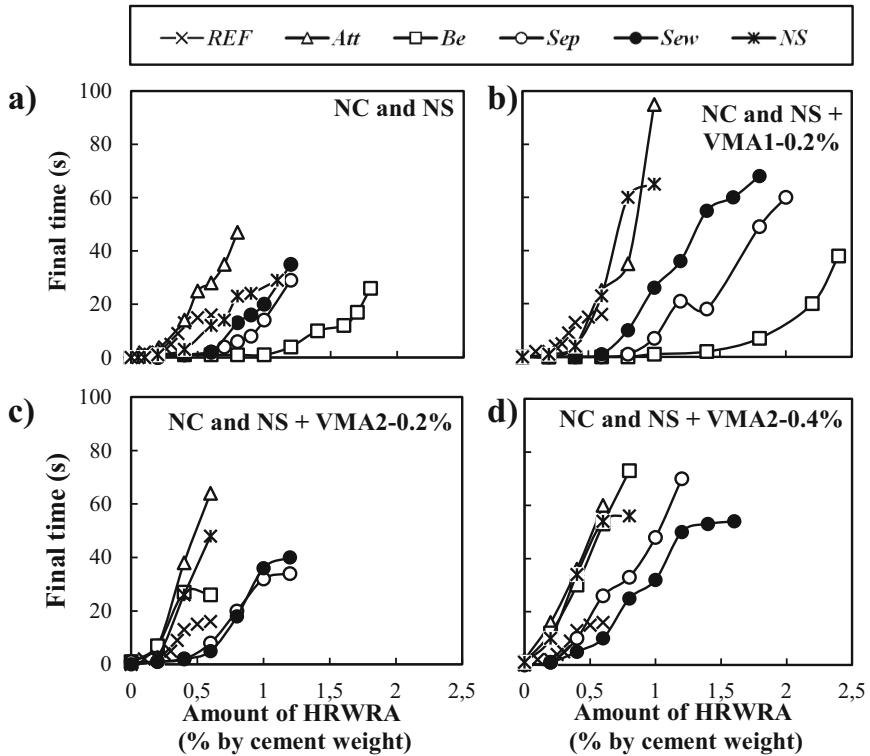


Fig. 2. Final time to spread results of mini-cone slump test. (a) Final time vs HRWRA% of pastes with NC and NS; (b) Final time vs HRWRA% of pastes with NC, NS and VMA1; (c) Final time vs HRWRA% of pastes with NC, NS and 0.2% of VMA2; (d) Final time vs HRWRA% of pastes with NC, NS and 0.4% of VMA.

calculated according to Roussel model [6] and Tregger model was used to calculate yield stress and viscosity [7]. The rheological parameters are summarized in Table 2.

4 Discussion

The combined use of nanoclays (NC), nanosilica (NS) and polymeric admixtures in cement paste produced some synergies which can modify the rheological properties of these pastes.

The incorporation of VMA1 in cement pastes enlarged the effects of NC and NS (Fig. 1b and 2b). These mixtures showed almost the same three behaviors than pastes without VMA1 (Fig. 1a and 2a). However, they required larger amounts of HRWRA due to the huge adsorption capacity of NC, NS and VMA1 [8, 14–16]. Thus, the adsorption capacity and the low water to binder ratio of 0.35 produced a larger necessity of HRWRA. Both, final spread diameter and final spread time results with VMA1 showed this behavior.

Table 2. Rheological parameters calculated using Roussel and Tregger models

Sample	Diameter mm		τ Pa (Roussel)		τ Pa (Tregger)		μ Pa s (Tregger)	
	0.2%	0.6%	0.2%	0.6%	0.2%	0.6%	0.2%	0.6%
HRWRA	0.2%	0.6%	0.2%	0.6%	0.2%	0.6%	0.2%	0.6%
VMA1-02ATT	110	235	506	11.4	2448	30	10.9	4.7
VMA2-02ATT	185	407.5	37	0.7	119	1.2	5.1	0.5
VMA2-04ATT	190	365	32	1.2	102	2.3	10.3	0.9
VMA1-02BE	100	100	824	824	4259	4259	19	19
VMA2-02BE	133	390	201	0.9	830	1.6	35	0.26
VMA2-04BE	155	327.5	92	2.2	333	4.3	25	1.46
VMA1-02SEP	100	105	854	669	4259	3207	19	14
VMA2-02SEP	105	10	669	230	3207	927	14	45
VMA2-04SEP	105	220	669	16	3207	43	14	7
VMA1-02SEW	100	110	854	530	4259	2448	19	10
VMA2-02SEW	100	160	854	81	4259	277	19	8.4
VMA2-04SEW	102.5	152.5	794	109	3690	367	16	22
VMA1-02NS	110	215	531	18	2448	50	10.9	7.2
VMA2-02NS	130	337	230	1.9	927	3.6	16	1.1
VMA2-04NS	160	347.5	81	1.7	277	3.1	17	1.1

On the contrary, the addition of VMA2 did not enlarge the effects of the nanocomponents. In fact, all *NC* and *NS* showed a similar behavior to pastes without VMA2 (Fig. 1c and d) with the exception of Bentonite (*Be*). VMA2 produced a sharp reduction of the HRWRA required by the paste with *Be* to spread. That synergetic effect was related to the capacity of VMA2 to restrain the *Be* adsorption capacity and the formation of the house-of-cards structure network typically attributed to *Be* [9, 14, 15, 19]. Besides, this effect was showed with both percentages of VMA2 0.2 and 0.4%. Nevertheless, pastes with 0.4% VMA2 and *Be* showed larger final time values than pastes with 0.2% of VMA2 and *Be*.

On the other hand, pastes with sepiolites showed similar behavior with both polymeric admixtures, VMA1 and VMA2. However, Sep showed a slight better compatibility with VMA2 while Sew performed better with VMA1. That could be due to the lower dispersion capacity of Sep in pastes with lower w/b ratios, requiring larger amounts of HRWRA. The large adsorption capacity of VMA1 than VMA2 made VMA2 a better option in this case. That effect did not happen with Sew because it is a functionalized product. However, Sew and VMA2 showed an undesirable interaction.

5 Conclusions

An experimental study on the synergies and interactions of several Nanoclays (*NC*), nanosilica (*NS*), a High range water reducing admixture (HRWRA) and two types of viscosity modified admixtures (VMA) on the rheological parameters of cement pastes

with limestone filler and 0.35 water to binder ratio was carried out, using the mini-cone slump test. The main conclusions of the study were:

- VMA1 intensified the effect of *NC* and *NS* on cement paste. Pastes with *NC*, *NS* and VMA1 required a higher amount of HRWRA than references without VMA1. The absorption capacity of VMA1 joint with the adsorption capacity of *NC* produced that effect.
- VMA2 (0.2 and 0.4%) decreased sharply the amount of HRWRA that paste with Bentonite (*Be*) needed to spread. VMA2 blocked the adsorption capacity of *Be* and produced a higher flowability with less amount of HRWRA. Moreover, the paste with *Be* and 0.4% of VMA2 increased the final time value. Clearly, VMA2 was able to modify yield stress and viscosity on paste with *Be*.
- Both sepiolites showed a similar behavior with polymeric admixtures. However, *Sep* presented a larger effectivity with VMA2 while *Sew* showed a larger effectivity with VMA1.
- VMA1 and VMA2 (0.4%) incremented final time values of all samples regardless the nanoclay type or the amount of HRWRA.
- Pastes with *NS* and *Att* showed almost the same behaviors with VMA1 and VMA2. Only showed a difference in the final spread time values with VMA1 in which *Att* presented higher values.

Acknowledgement. Financial support was provided by NanoCompac (BIA2016-77911-R), funded by the Spanish Ministry of Economy and Competitiveness. The authors greatly acknowledge the support of the companies TOLSA GROUP S.A, BASF construction chemicals, Omya Clariana and Cementos Portland Valderrivas.

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Geopolymer Formulation for Binder Jet 3D Printing

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Abstract. The construction industry is a significant emitter of CO₂ and it uses more than 40% of the resources consumed worldwide, which are becoming scarce. 3D printing can help to reduce the material consumption by enabling the manufacturing of structurally optimized building parts and formworks since material is only placed where needed. To combine the reduction of material consumption with less CO₂ emissions, the raw materials that are currently used in 3D printing in construction need to be replaced by materials with lower carbon footprint. Among the materials with high potential for this application, geopolymer is a good candidate to fulfill the required criteria in terms of performances and embodied energy as they can be built from waste materials such as slag, fly ash or glass waste as aluminosilicate source.

The objective of this research is thus to define a mix design strategy to allow the implementation of geopolymers in powder bed 3D printing with various waste materials. In this technique, an aluminosilicate powder bed is activated through the deposit of an alkaline silicate solution. This selective binder activation approach requires to master the spreading of the liquid into the powder bed and to ensure that the reaction takes place where it is needed. A series of experiments at the droplet level were performed to estimate the relationship between the initial liquid to solid ratio and the packing of the powder bed. Based on this a mix design strategy for the printing solution was developed and proofed by SEM/EDX analysis.

Keywords: Powder bed 3D printing · Geopolymers · Mix design · Sustainability

1 Introduction

The construction industry causes massive CO₂ emissions and consumes more than 40% of the resources available worldwide [1, 2]. In the last decades, the operational energy of buildings could be reduced by more efficient thermal insulation [3], but what is still left is the embodied energy of the material. With 3D printing and additive manufacturing, structurally optimized building parts and formworks can be printed [4, 5]. Therefore, this new building technique can help to reduce the embodied energy in

buildings by reducing the amount of used material. The energy consumption is further reduced if the printed materials have a low carbon footprint, such as geopolymers, which can be built from waste materials. A geopolymer is an inorganic, amorphous material, consisting of a silica-alumina network, charge compensated with sodium or potassium [6–8]. Geopolymers are synthesized from the activation of aluminosilicate with an alkaline solution. Metakaolin is the most common aluminosilicate source, but waste materials such as fly ash, slag, brick powder, glass waste and many more can also be used. Geopolymers are defined by their Si/Al, Na/Al, $\text{SiO}_2/\text{Na}_2\text{O}$, and $\text{H}_2\text{O}/\text{Na}_2\text{O}$ ratios that determine the setting time and the strength of the material [9, 10]. With Si/Al between 2 and 2.5, and Na/Al between 1 and 1.5, the strength of a geopolymer is comparable to concrete [10]. In a casted geopolymer, an alkaline solution is mixed with an aluminosilicate in the right proportions to obtain the desired properties.

In previous work, we could show that the commonly used organic binder in powder bed 3D printing can be replaced by a geopolymer [11]. In comparison with Xia *et al.* [12], who used a selective binder approach [13], only the aluminosilicate is mixed with the sand in the powder bed, and the alkaline solution is spread on top to locally synthesize a geopolymer (*cf.* Fig. 1). This has the advantage that the powder bed is not affected by moisture and no curing is necessary.

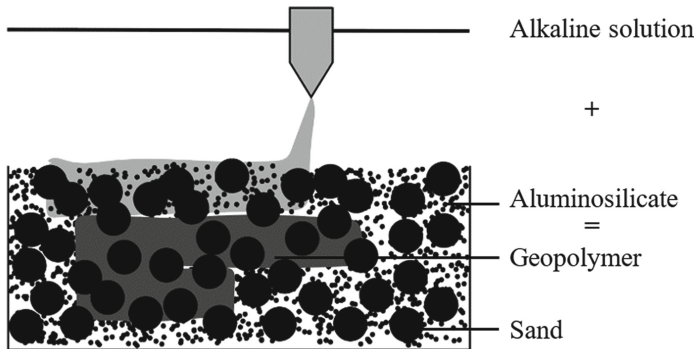


Fig. 1. Geopolymers in binder jet 3D printing.

In comparison with the casting of a strong geopolymer, where all the components are mixed with the desired ratios, in binder jet 3D printing, the local composition of the geopolymer depends on the penetration of the printing liquid into the powder bed.

Therefore, the composition of the printing solution needs to be adapted according to its penetration behavior through the powder bed and the targeted composition of the final geopolymer. Figure 2 illustrates the differences in geopolymer mix design between traditional casting and powder bed 3D printing.

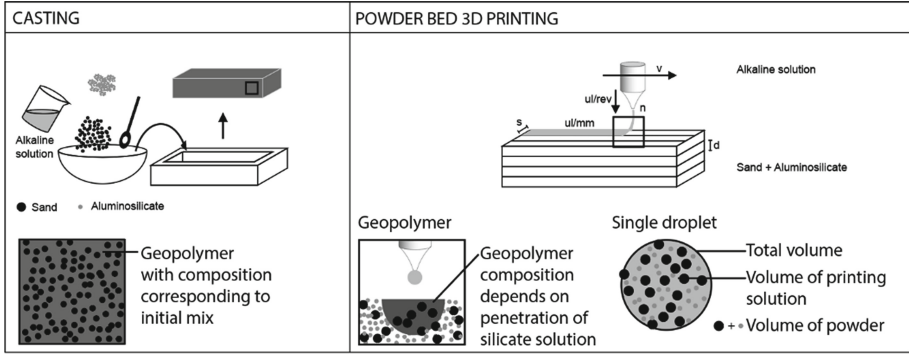


Fig. 2. Comparison between mix design for casting and binder jet 3D printing.

To simplify the implementation of alternative aluminosilicates and sand substitutes in powder bed 3D printing with geopolymers, an applicable mix design strategy is needed.

Assuming the liquid to fill all the voids when penetrating a powder bed with known composition, the liquid to solid ratio can be expressed as a function of the porosity of the powder bed. Therefore, the volume of liquid that reaches a certain amount of metakaolin is known. From this and the desired Si/Al and Na/Al ratios in the final geopolymer, the composition of the printing solution ($\text{H}_2\text{O}/\text{Na}_2\text{O}$ and $\text{SiO}_2/\text{Na}_2\text{O}$ ratios) can be calculated. To proof whether a solution with the calculated composition printed on the given powder bed results in the desired geopolymer, the composition of printed samples was analyzed by Scanning Electron Microscope (SEM) coupled with Energy-dispersive X-ray spectroscopy (EDX). Additionally, with the same solution and powder bed, single droplets were produced to verify if the composition is the same at the droplet level and in the print. To test whether the calculated liquid to solid ratio of the chosen materials leads to the desired Si/Al and Na/Al, a corresponding sample was mixed and cast. The samples for comparison were tested in SEM/EDX as well.

2 Materials and Methods

2.1 Alkaline Solution Composition

In previous work, single droplets of printing solution were deposited on powder beds with varying aluminosilicate content, and the dried droplets were analyzed by microtomography [11]. From these images, it seemed that in the center of the droplets, the liquid occupies all the voids in the powder bed. Therefore, the volume of the liquid V_l can be assumed equal to the volume of the voids V_v :

$$V_l = V_v = \varepsilon * V_T \quad (1)$$

Where ε is the dense porosity of the powder bed. With the total volume $V_T = V_p + V_l$, V_p being the volume of powder, the liquid to solid ratio can be expressed as a function of ε :

$$\frac{V_l}{V_p} = \frac{\varepsilon}{1 - \varepsilon} \quad (2)$$

Knowing the specific densities of the liquid and the powder (ρ_l and ρ_p), the liquid to solid ratio in mass can be determined as follow:

$$\frac{m_l}{m_p} = \frac{\varepsilon \cdot \rho_l}{\rho_p(1 - \varepsilon)} \quad (3)$$

The powder bed consists of 20 wt% metakaolin (Metastar501 from Imerys, here referred to as MK, mean grain size d_{50} of 4 μm) and silica sand (Quartz sand FS003 from Strobel Quartz Sand GmbH, mean grain size d_{50} of 240 μm). The dense compacity (57%), porosity (43%), and density (1.45 g/cm^3) of the powder mix were measured according to Lédée *et al.* [14]. This results in a liquid to solid ratio of 0.4 (Eq. 3). To obtain a strong geopolymer, a Si/Al ratio of 2 and a Na/Al ratio of 1.2 [10] was targeted. Therefore, knowing the silica and alumina content of the metakaolin (51.63 wt%, and 44.37 wt%, respectively, measured with X-Ray Fluorescence), and the liquid to solid ratio, the $\text{H}_2\text{O}/\text{Na}_2\text{O}$ and $\text{SiO}_2/\text{Na}_2\text{O}$ ratios in the printing solution were determined to be 13.9, and 1.7 respectively. The specific density of the solution (1.46 g/cm^3) was measured with a Densito 30 PX (Mettler Toledo).

2.2 Powder Bed 3D Printing

Samples of dimension $4 \times 4 \times 16$ cm were printed in a self-built 3D printer (cf. Fig. 3), designed with affordable and easily accessible components [15]. This setup allows the use of a range of materials by controlling different parameters: nozzle diameter (0.25 mm), injection volume per distance (0.6 $\mu\text{l}/\text{mm}$), the spacing between printed lines (0.75 mm), and the layer height (3 mm). After 24 h the samples were taken out of the powder bed and 7 days after printing, the compression strength was measured with a mechanical press (Matest, Switzerland) using a 50 kN cell, applying 0.1 kN/s.



Fig. 3. Powder bed 3D printing with geopolymers

2.3 Single Droplet

To study the penetration of the liquid into the powder bed, single droplets of printing solution (10 μl) were dropped with a pipette on the same powder bed as in 3D printing (*cf.* Fig. 2). The droplets were dried at room temperature and extracted from the powder bed. These droplets serve as fast and easy samples without printing a full piece.

2.4 Casting

For comparison reasons, three geopolymer samples were cast with a liquid to solid ratio of 0.4. This ratio corresponds to the ratio calculated from Eq. 3. The dry components (MK and sand) were mixed with the corresponding solution for 2 min in an automatic planetary mixer (Matest, Switzerland), poured into a mold and cured at room temperature for 7 days before being tested on compression.

2.5 SEM/EDX

Droplets and pieces of 3D printed and cast samples were embedded in epoxy, polished to 1 μm and coated with a carbon coating.

An EDX analysis (on a Quanta 200 3D instrument) was performed on up to 10 points on the geopolymer matrix of each sample to determine the Si, Al and Na atomic percentages. From these values, the Si/Al and Na/Al ratios on the corresponding points were calculated.

3 Results

Figure 4 shows the SEM images of the bottom of a single droplet, and cross-sections of a 3D printed and a casted bar. In the graph in Fig. 5, the average of the measured Si/Al and Na/Al ratios for the single droplet (2.2 ± 0.3 ; 0.7 ± 0.4), the 3D printed bar (2.1 ± 0.1 ; 0.6 ± 0.1), and the casted bar (2.2 ± 0.2 ; 0.8 ± 0.2) are plotted. They show a close fit to the targeted Si/Al value of 2, whereas the measured Na/Al ratio is lower than expected (0.7 instead of 1.2). The average compression strength of the 3D Printed bars was 3.3 MPa with a standard deviation of 0.7 MPa, whereas the casted bars reached an average of 35 ± 4.8 MPa.

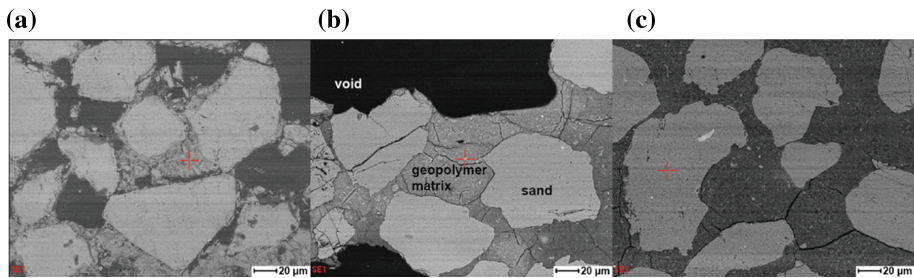


Fig. 4. SEM images of single droplet (a), 3D printed bar (b), and a casted bar (c)

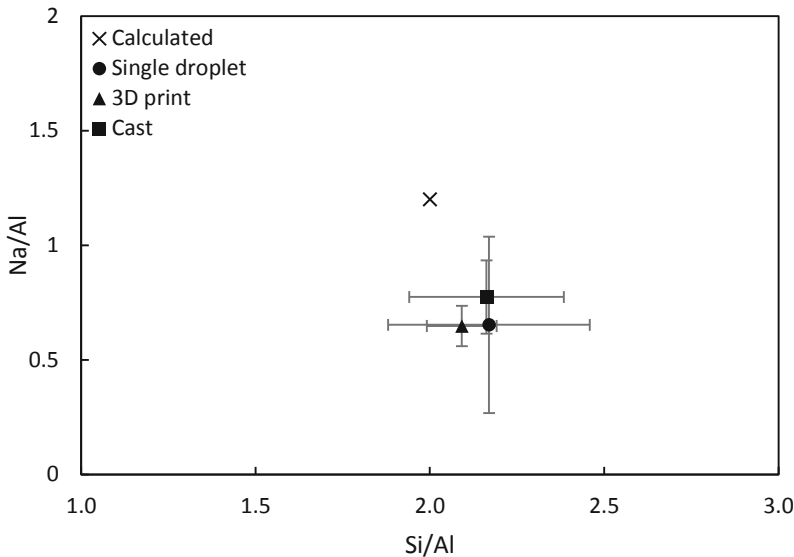


Fig. 5. Si/Al and Na/Al ratios of single droplets, printed and cast samples, measured by EDX

4 Discussion

The Si/Al and Na/Al ratios measured with EDX are similar in all the three samples; they lay in each other's standard deviation. Therefore, a geopolymer with the same composition is built no matter whether only a single droplet or a full part is printed, and the single droplet can be used as an example for fast testing of solutions. The fact that the 3D printed and the cast sample have the same composition, confirms the theoretical assumption for the liquid to solid ratio in the 3D print. However, it is important to note that this only applies to a local level of the print (*cf.* Fig. 6). Overall, the print is more porous than the casted material, due to the unreacted powder present in the sample. But, the results show that where the binder is printed, the composition can be modeled by the behavior of a single droplet.



Fig. 6. Close up sketch of a casted sample compared to a 3D print of the same material

The calculated values for Si/Al and Na/Al ratios correspond to the initial mix composition of the casted samples. The discrepancy between this value and the values measured with EDX is similar as found by Rowles *et al.* [10]: the Si/Al ratios are higher, and the Na/Al ratios lower as expected from the initial composition of the mix. The slight shift towards higher Si/Al ratios could be explained by the presence of not fully reacted metakaolin. The measured Na/Al ratios are lower than the calculated value. Due to the evaporation of lightweight atoms under electron beam impact, the Na content might be underestimated, resulting in a measured Na/Al ratio lower than expected.

However, due to time reasons, the EDX analysis was performed only at 10 different points. A scan on a larger surface will be performed in order to test the validity of the small number of measurements.

The average compression strength of the printed samples was 3.3 MPa, which is clearly lower than the casted samples, reaching 35 MPa on average. The overall density in 3D printing is lower than in casting, therefore the lower compression strength can be explained. In the meanwhile, the printing process could be improved and samples with up to 12 MPa compression strength were printed with the same material. A dimensional precision of 5% in x and y direction, and 7% in z-direction was reached with high accuracy. The improvement was possible due to an enhanced pump, which allows more precise liquid distribution, as well as stronger vibrators to distribute a more homogeneous powder bed. This enhanced strength is still not in the range of conventional building materials, such as concrete or wood. But, it can be applied in structurally optimized load bearing building parts, which are loaded only on compression and therefore don't require strong materials [16]. The density of the 3D printed

geopolymers (1.5 g/cm^3) is in the range of a lightweight concrete, whereas its compression strength is lower. To improve the performance of the locally printed geopolymer, the mix design of the printing solution could be adapted by targeting higher Na/Al values, in order to have less unreacted metakaolin.

5 Conclusion

With this series of experiments, it is possible to validate the proposed mix design strategy to implement geopolymers in powder bed 3D printing. Only knowing the porosity and the specific density of the powder bed, and the specific density of the liquid, the composition of the printing solution can be determined in a way to obtain desired Si/Al and Na/Al ratios in the printed geopolymer. Thanks to this approach, any waste powder grain can be incorporated in the process and replace sand, which is becoming scarce.

The method can also give an idea of the solution composition when alternative aluminosilicates (such as fly ash, slag or brick powder) are used. In this case, adaptations have to be made due to the different reactivity of the aluminosilicates.

The next steps will be to adapt the printing solution for the metakaolin system to optimize the composition allowing the printed geopolymer to reach high final strength. Further, the method will be extended to alternative systems using waste grains instead of quartz sand and alternative aluminosilicates.

Acknowledgments. Financial support by the Swiss National Fund (SNF) and the NCCR in digital fabrication is gratefully acknowledged (project N°200020_169359). The authors would like to thank Asel Maria Aguilar Sanchez for the support with the SEM/EDX sample preparation and measurement.

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Lightweight Concrete 3D Printing by Selective Cement Activation – Investigation of Thermal Conductivity, Strength and Water Distribution

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Abstract. The 3D printing technology Selective Cement Activation (SCA) is a particle-bed-based additive manufacturing method in which a dry mixture of sand and cement is spread in thin layers and solidified with water. SCA allows the production of complex and high-resolution components without the necessity for additional support structures. One drawback of concrete 3D-printing for free formed facade elements has been the need for additional thermal insulation to fulfil relevant building requirements. This causes an additional economic and ecological effort to create custom-built insulation to fit the 3D facade. Therefore, this paper discusses the fabrication of lightweight concrete through SCA by replacing the sand (S) with lightweight aggregates (LA, expanded glass beads) in order to decrease the thermal conductivity. However, the open pore structure of the lightweight aggregate could also change the water distribution behavior between the layers which would positively affect the hydration process.

Test series with different w/c-ratios (0.3, 0.4 and 0.5) and type of aggregate (S and LA) were produced. Additionally, the test series with LA were fabricated without and with methylcellulose to further increase water absorption. The strength (compressive and flexural) and thermal conductivity were measured direction dependent to take anisotropic effects into account. Additionally, the water distribution perpendicular to the layers was determined using ¹H-NMR.

Specimens produced with LA showed a 3.5 to 4.4 times lower thermal conductivity compared to the specimens produced with S. However, using LA affected the density and thus the strength values of the material. Additionally, the open pore structure of the LA affected the water distribution between the layers which lead to an increase in strength with decreasing w/c-ratio. This is contrary to previous experiments using SCA and sand where strength has improved with increasing w/c-ratio [1–3].

Keywords: Lightweight concrete · Additive manufacturing · Particle-bed · 3D printing · Selective cement activation · SCA · Selective binder activation

1 Introduction

Additive manufacturing (AM) of concrete structures provides new possibilities for the construction and design of buildings. With AM methods highly complex structures can be realized. This offers the possibility in optimizing load bearing elements which leads to a high potential for material savings. Furthermore, no formwork is needed and thus waste is reduced. These aspects can help to decrease the environmental and economic impact of concrete construction, see amongst others [4–7]. However, in regions with colder climates exterior wall elements require additional thermal insulation which generates extra effort during construction as well as during recycling at the building's end of life. A possible solution to this problem is the use of lightweight concrete instead of common concrete in the additive manufacturing process. Henke et al. as well as Matthäus et al. [8–12] showed that it is possible to produce exterior wall elements without additional thermal insulation through additive manufacturing by concrete extrusion.

The aim of this paper is to fabricate lightweight concrete structures by using the AM method Selective Cement Activation – SCA [1–3]. Compared to concrete extrusion SCA allows the production of objects with a higher surface resolution in combination with a high complexity of the printed parts due to the supporting ability of the unbound material in the building volume. The investigations address a comparison of the thermal insulation behavior of lightweight SCA concrete and common SCA concrete. Furthermore, the mechanical strength of the concrete (compression and flexural) is examined. However, the open pore structure of the lightweight aggregates (expanded glass beads) could change the water distribution between the layers. This effect is also considered in this paper.

2 Methods and Materials

2.1 Methods

Selective Cement Activation – SCA is a particle-bed based additive manufacturing (AM) technique, which bonds thin layers of a cement-aggregate mixture by selectively applying water to those areas where the material is intended to harden.

For this paper, an experimental SCA printer with 32 nozzles and an internal area of $450 \times 600 \text{ mm}^2$ was used. The layer thickness was set at 1 mm and the water pressure was adjusted between 0.3 and 0.8 bar depending on the w/c-ratio. A more detailed description of the printer can be found in [13].

For the measurements of strength and thermal conductivity prisms with a size of $40 \times 40 \times 160 \text{ mm}^3$ were printed in two print directions, either with the long side of the prism oriented parallel (PD-0°) or perpendicular (PD-90°) to the print direction (see Fig. 1).

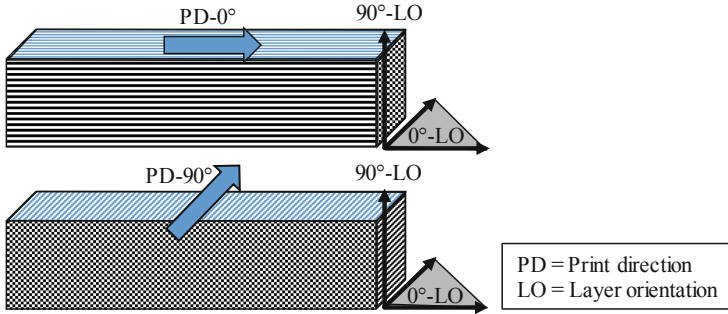


Fig. 1. Print direction and layer orientation of the printed prisms

The specimens were stored in the particle-bed for 3 h. After the excavation, the prisms were stored for 1 d at 20 °C/ ~100% R.H. From day 2 on, the specimens cured under laboratory atmosphere (20 °C/ ~60% R.H.) until testing, see Fig. 2.

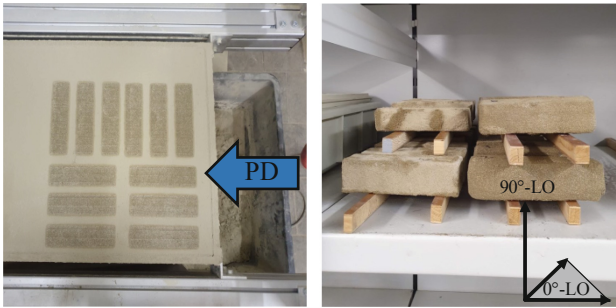


Fig. 2. Left: Prisms after printing still within the particle-bed, right: excavated specimens stored under laboratory atmosphere.

The compressive and flexural strength were determined after 7 d and 28 d according to EN 196-1:2016-11 with the load direction along 90°-LO.

The thermal conductivity was measured parallel to the layers (0°-LO) and perpendicular to the layers (90°-LO), see Fig. 1, on dried prisms using a Hot Disk TPS 1500 with a probe disk with a radius of 6.4 mm (Kapton 5501). The output power was 50 mW and the measurement time 80 s.

¹H-NMR was used to detect unbound water within the specimens to determine the water distribution between the layers. The measurements were conducted after 3 h, 6 h, 8.5 h, 1 d, 7 d, 28 d and in dry (dried at 40 °C until mass constancy) as well as in wet condition (stored under water at 20 °C until mass constancy) with a NMR-Mouse (KEA, magritek) using a PM25-C30-15 mm probe head and an Inverse-Laplace fit. The water distribution was determined perpendicular to the layers on specimens with a size of approx. 60 × 60 × 18 mm³ with a resolution of 200 μm for the first 7 mm of the printed specimens. The amount of the unbound water (vol%) was calculated by picking the first peak of the volt amplitude [arb. u.] of every depth step and converted with the ratio of the wet/dry mass related to the mean value of the wet ¹H-NMR signal.

2.2 Materials

The dry mixture in the particle-bed consisted of 40 vol% OPC (52.5 N) and 60 vol% (envelope volume, including internal porosity of the aggregates) aggregate with a maximum grain size of 0.5 mm. For the series produced with “normal” aggregate, quartz sand (S) with a grain size of 0.1 – 0.5 mm (particle density 2650 kg/m³) was used. In the series manufactured with lightweight aggregate (LA) the sand was replaced by expanded glass beads (0.25 – 0.5 mm, particle density 700 kg/m³) by the same (envelope) volume. Additionally, test series with 1.75% by weight of cement (wt%) methylcellulose (T) were prepared to determine its effect on strength at varying water content. Methylcellulose has already successfully been used to increase shape accuracy of SCA specimens in [3].

For the activation of the binder, pure deionized water was jetted onto the surface of the particle-bed.

For the thermal conductivity measurements, three test series with constant w/c-ratio 0.4, produced with sand (S0.4) and lightweight aggregate without and with methylcellulose (LA0.4 and LA0.4T) were compared.

To examine the effect of the water content on the mechanical performance, the compressive and flexural strength of the material after 7 and 28 d was determined on specimens with a w/c-ratio of 0.3, 0.4 and 0.5 for S and LA (without and with T). However, it should be noted, that using different w/c-ratios and water application pressures in the printing process can lead to an inhomogeneity in the hardened specimens [3].

Furthermore, a measurement of the water distribution was conducted using ¹H-NMR for the series S0.5 and LA0.5.

The compositions of the test series are presented in Table 1.

Table 1. Mix design of the test series

Series	w/c-ratio	Particle-bed composition			
		Cement	Aggregate		Methylcellulose
			S	LA	
[-]	[-]	[vol%]	[vol%]	[vol%]	[wt% by cement]
S0.3	0.3	40	60		
S0.4	0.4	40	60		
S0.5	0.5	40	60		
LA0.3	0.3	40		60	
LA0.4	0.4	40		60	
LA0.5	0.5	40		60	
LA0.3T	0.3	40		60	1.75
LA0.4T	0.4	40		60	1.75
LA0.5T	0.5	40		60	1.75

3 Results and Discussion

3.1 Thermal Conductivity

Figure 3 left shows the measurement of the thermal conductivity of printed specimens with a w/c-ratio of 0.4 fabricated with sand (S0.4), lightweight aggregate (LA0.4) and lightweight aggregate with additional methylcellulose (LA0.4T) in relation to the layer orientation (see Fig. 1). Figure 3 right displays the density of the measured specimens.

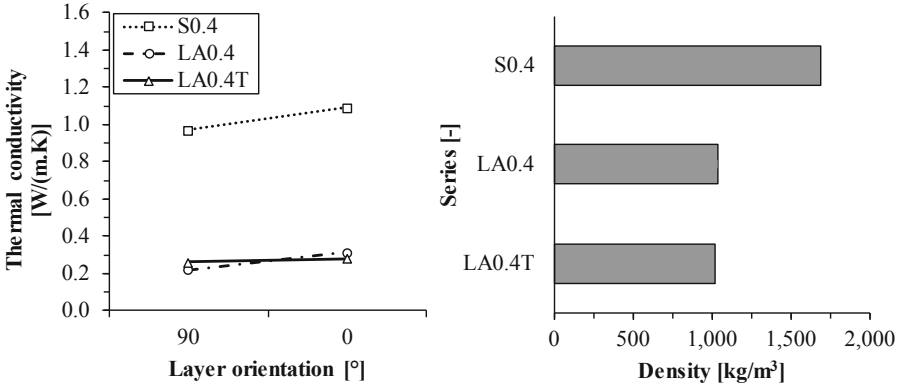


Fig. 3. Left: Thermal conductivity and right: Density of dry SCA specimens

The specimens with sand (S0.4) show a 3.5 to 4.4 times higher thermal conductivity compared to the specimens produced with lightweight aggregate (LA0.4 and LA0.4T), see Table 2. The measured thermal conductivity between 0.22 and 0.31 W/(m.K) of LA0.4 and LA0.4T is caused by the low density of 1,040 kg/m³ and 1,015 kg/m³. These results are also in line with the results of the printed lightweight concrete in [8, 9]. There, Henke et al. produced a lightweight wood chip concrete with a density of 995 kg/m³ and a thermal conductivity of 0.25 W/(m.K).

Table 2. Thermal conductivity of the test series

Series	Layer orientation	Thermal conductivity	Specific heat	Density
[–]	[°]	[W/(m.K)]	[MJ/m ³ K]	[kg/m ³]
S0.4	90	0.97	5,868	1,692
	0	1.09		
LA0.4	90	0.22	3,749	1,040
	0	0.31		
LA0.4T	90	0.26	2,745	1,015
	0	0.28		

However, due to the low density of $1,692 \text{ kg/m}^3$ S0.4 can already be classified as a lightweight concrete ($\leq 2000 \text{ kg/m}^3$). Therefore, the thermal conductivity of the sand specimen S0.4 is more than 2 times lower than the thermal conductivity of a common concrete with an aggregate volume ratio of 0.6 and a w/c-ratio of 0.4 [14]. The low density of the S0.4 specimens can likely be explained by a non-optimized particle size distribution and insufficient compaction of the particle-bed by the linear compaction roller of the printer.

An interesting detail is that there seems to be a slight dependency of the thermal conductivity on the layer orientation. This effect increases with increasing thermal conductivity as well as specific heat of the material which could be explained by the formation of “tunnels” in the printing direction due to the pressure of the water jet. This leads to a inhomogeneous distribution of the density over the height of the specimens and layers with more dense zones parallel to the layer orientation [3]. This, in turn, leads to an increased thermal conductivity in LO-0°. However, the porosity of the “dense zones” probably increases with the substitution of S with LA and continues to increase with the use of methylcellulose [15].

3.2 Strength and Water Distribution

Figure 4 shows the compressive strength (left) and the flexural strength (right) at a concrete age of 7 days depending on the w/c-ratio. Figure 5 shows the results of the ^1H -NMR measurements of the water distribution in a specimen produced with sand (above) and with lightweight aggregate (below), both with a w/c-ratio of 0.5.

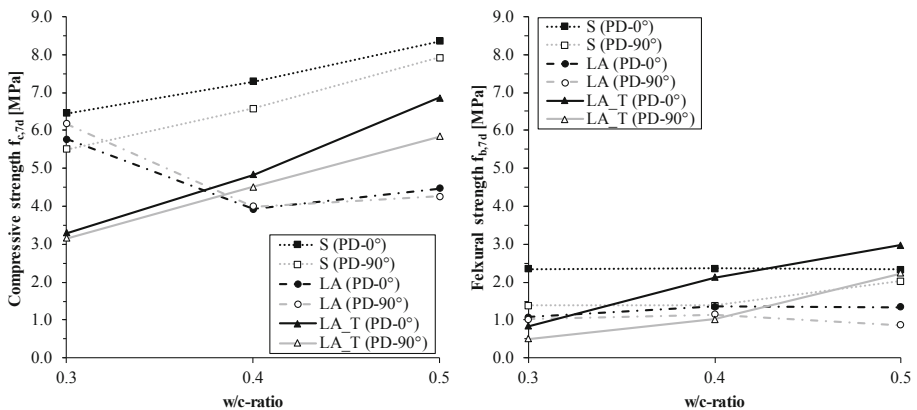


Fig. 4. Compressive and flexural strength after 7d

The compressive strength of the sand specimens (S) and the compressive as well as the flexural strength of the lightweight aggregate specimens with methylcellulose (LA_T) increase with increasing w/c-ratio. Same tendencies can also be found in Lowke et al. [1–3] for sand specimens. There, the authors explained this phenomenon by an uneven water distribution between the layers caused by the process technology

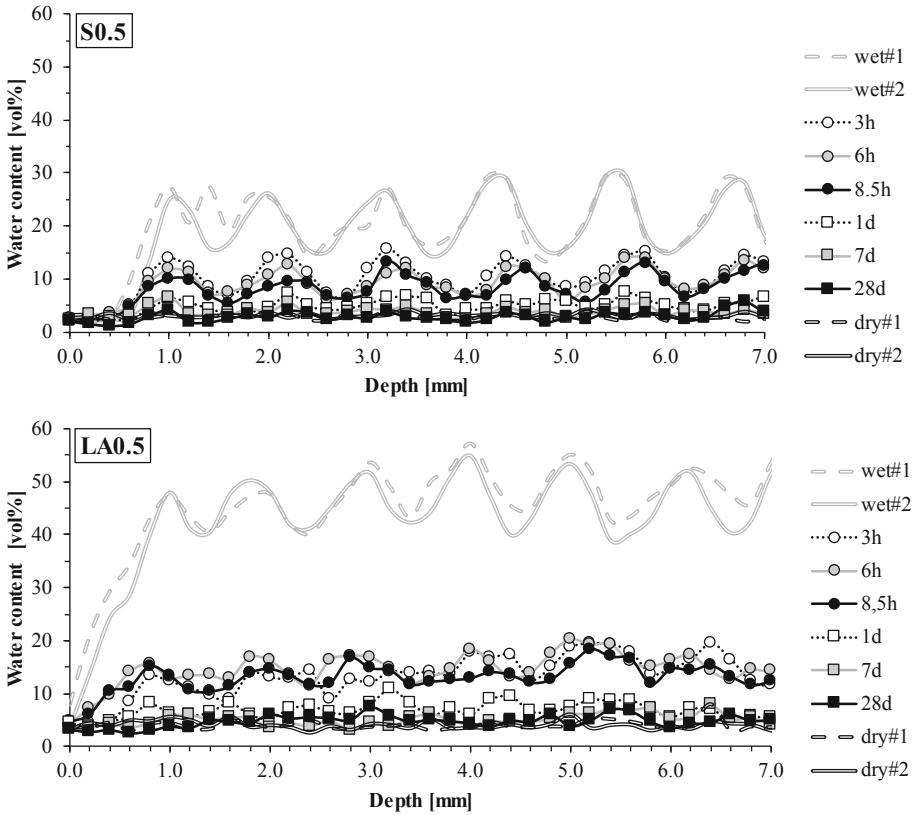


Fig. 5. Water content [vol%] of a specimen printed with a w/c 0.5 and sand S (top) and lightweight aggregates LA (bottom)

and a more even water distribution (and hydration) across the layers with increasing w/c-ratio due to the increased water supply. The uneven water distribution can also be found in Fig. 5, left.

As expected, due to the lower density, the LA and LA_T specimens show decreased strength values compared to the S specimens. However, the LA specimens exhibit the opposite strength development in dependency of the w/c-ratio when compared to the S and LA_T specimens. The compressive strength decreases with increasing w/c-ratio which is the expected strength development of concrete. This can be explained by the open pore structure of the lightweight aggregate which causes a more even water distribution similar to a regular concrete mixture. This can be verified by the ^1H -NMR measurements in Fig. 5. There, the open pore structure leads to a much higher water storage capacity (55 vol% water for LA and only 30 vol% water for S specimens) of the wet specimens. Furthermore, the suction ability of the LA causes a higher mean water distribution as well as a smaller deviation of the water between the layers in the first 24 h after printing (LA: 15.8 ± 4.5 vol% and S: 11.5 ± 3.8 vol%).

Therefore, the concrete technological correlations predominate and the process generated weak spots recede into the background.

Furthermore, the water bonding capacity of the methylcellulose (LA_T) seems to be higher than the water attraction of the LA. This could cause a more local water concentration and the reverse of the strength behaviour of the LA_T specimens to the sand specimens (S).

Additionally, the application of methylcellulose (LA_T) leads to an increase in strength compared to the LA specimens without T for higher amounts of water ($w/c \geq 0.4$). This can be explained by the combination of two effects: The more even water distribution due to the LA and the limitation of the water suction across the boundary of the specimen's geometry as an effect of T. This leads to a concentration of the water within the designated dimensions of the specimen leaving the full amount of water available for hydration. Lowke et al. showed this effect also for sand specimens in [3].

All specimens show a slight anisotropic behavior which is caused by the print direction. The high speed of the individual water jets leads to a slight displacement of the binder material between the aggregates which may afterwards act as weak spots. These are less favorable for the 90° print direction.

However, all these effects seem to be less pronounced for the flexural strength (except for the LA_T specimens). This is probably caused by the relatively low number of only three tested specimens for each layer and printing direction, the low flexural strength values and the comparatively high deviation.

The results after 28 d showed similar tendencies and strength levels which can be expected by the reaction kinetics of the cement type.

4 Conclusion and Outlook

This paper investigates the effect of using lightweight aggregate (LA) instead of sand (S) on the thermal conductivity, strength and water distribution of concrete, 3D-printed by Selective Cement Activation. The following main findings were observed:

- Thermal conductivity could be decreased by 3.5 to 4.4 times by using LA instead of S.
- Additional use of methylcellulose does not improve the thermal insulation behavior of investigated LA elements.
- Specimens showed a slight anisotropy of the thermal conductivity as an effect of the layer orientation.
- Even the S specimens showed a more than 2 times lower thermal conductivity than common concrete due to its low density.
- Using LA instead of S leads to a more equal water distribution and a higher mean water content between the layers.
- Using LA instead of S causes a predominance of the concrete technological over the process technological correlations which leads to increased strength with decreasing w/c-ratio (SCA specimens usually show the opposite behaviour)

- Application of methylcellulose increases the strength for a w/c-ratio ≥ 0.4 for LA structures.

The application of LA to produce lightweight and high thermal insulating structures was successful. The low thermal conductivity allows the production of exterior wall elements without the need for additional insulation. However, the strength values of the material have to be increased for practical application. Therefore, cement mixtures (with alternative binder compositions) in combination with methylcellulose and further investigations on water distribution (e.g. with $^1\text{H-NMR}$) can be useful. Furthermore, the particle size distribution of the dry mixture has not been optimized for this paper. An optimized packing density in combination with other types of lightweight aggregates could further increase the strength of the material.

Acknowledgements. The investigations of this paper were conducted within a DFG (German Research Foundation) knowledge transfer project “Industrial 3D Concrete Printing by Selective Cement Activation - Process, Material, Applications” (project number 389705984).

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Rheology and Fresh State Behaviour



Numerical Model Describing the Early Age Behavior of 3D Printed Concrete – Work in Progress

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Abstract. A numerical model used to predict the behavior of 3D printed concrete in the early age phase up until the point of collapse is presented. An incremental creep model for the material including aging and temperature effects is suggested. Furthermore, kinematic nonlinear effects are included in order to predict instability. The input parameters to the numerical model are determined through an optimization process where the displacement error between a finite element method (FEM) model and digital image correlation (DIC) measurements from an actual 3D print are minimized. A simplified (current state) version of the suggested numerical model was used to predict at how many layers a specific 3D print collapsed, with an error of 58%. This was concluded to be expected, since the numerical model is not fully implemented yet.

Keywords: 3D concrete print · Creep · Digital image correlation · Finite element method · Optimization loop

1 Introduction

Additive manufacturing, also known as 3D printing, has experienced a rapid development over the past decades within the construction industry, see e.g. Buchanan and Gardner (2019). The principle of the method consist in using an automated process to construct a defined 3D model by sequentially adding layers on top of each other.

In the concrete industry the method is often referred to as 3D concrete printing (3DCP). However, one of the major challenges in 3DCP is the absence of formwork, which implies that the printed concrete should be able to carry it's own weight (and potential exterior loads) immediately upon printing. Otherwise collapse may occur. This requirement is typically referred to as buildability, cf. Buswell et al. (2019).

To prevent collapse during printing, knowledge about the concrete behavior in the early age stage is required. For this purpose, analytical and numerical models using input parameters from experimental tests can be used. Wolf et al. (2018) and Wolf et al. (2019) used ABAQUS with input parameters determined from triaxial compression tests and shear tests models to predict the mechanical behavior of 3DCPs in the early age stage. Mohr-Coulomb yield criteria and global buckling conditions were included

in the models in order to predict collapse. Suiker (2018) introduced a so-called mechanistic model for straight walls that included a plastic yield condition and elastic buckling to describe the collapse modes. Finally, Kruger et al. (2019) proposed an analytical lower bound model based on a Mohr-Coulomb material with rheological material parameters as input.

Common for all of the mentioned 3DCP references is that they report good agreement between their suggested models and actual 3DCP tests. However, there is still room for improvement in the modelling.

In the present paper a novel numerical model to describe the early age behavior of 3DCP is suggested. The 3D print is modelled in the commercial software ABAQUS including a constitutive model describing a viscoelastic material on incremental form. The model input parameters are initially determined from conventional concrete tests and then subsequently adjusted through an optimization loop minimizing the difference in the displacements predicted by the ABAQUS model and displacement measurements performed by Digital image correlation (DIC) on the 3D print.

The novelty of the present work consist in the optimization of the input parameters by use of DIC measurements and the use of an incremental viscoelastic model. The suggested model is, however, currently in its implementation phase. Thus, the current paper is written to present the ideas of the suggested model and to illustrate its principles by use of a simple (current state) model.

2 Numerical Model Definition

The suggested model is comprised of the following elements: i) A numerical model in the commercial FEM program ABAQUS including kinematic nonlinear effects, ii) an incremental constitutive equation iii) and an optimization loop used to fit the input parameters. In the following a descriptions of the applied constitutive model and the optimization loop are given.

2.1 Incremental Constitutive Equation

The constitutive equations are considered on incremental form. The general form is given as, see e.g. Bazant et al. (1997);

$$\underline{\hat{\sigma}} = \underline{\underline{D}}_t(\underline{\hat{\epsilon}} - \underline{\hat{\epsilon}}_k) \quad (1)$$

Where $\underline{\hat{\sigma}}$ represents the stress increment vector, $\underline{\underline{D}}_t$ is the constitutive material tangent stiffness matrix, $\underline{\hat{\epsilon}}$ is the total incremental strain vector and $\underline{\hat{\epsilon}}_k$ is the incremental strain vector from e.g. creep, shrinkage and thermal gradients.

In the present study the 3DCP material is considered a viscoelastic material represented by a rheologic model. In the given case a generalized Maxwell material with N branches (each containing a springs and a dashpot in series) is considered, see Fig. 1.

$\underline{\underline{D}}_i(t, T)$ and $\underline{\underline{\eta}}_i(t, T)$ represent a stiffness matrix and a viscosity matrix of the i 'th branch, respectively. All parameters are functions of time, t , and temperature, T .

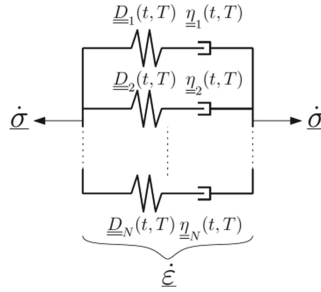


Fig. 1. Maxwell material dependent on time, t , and temperature, T .

Following the principles of the work in Bazant et al. (1997) it is possible to arrange a differential equation governing the total strain increments for each of the N generalized Maxwell branches. These are;

$$\dot{\epsilon} = \underline{\underline{D_i^{-1}}} \left[\left(\dot{\eta}_i + \underline{\underline{D_i}} \right) \dot{\epsilon}_i^d + \underline{\underline{\eta_i}} \ddot{\epsilon}_i^d \right], \quad i \in [1, N] \quad (2)$$

where $\dot{\epsilon}_i^d$ and $\ddot{\epsilon}_i^d$ represent the i 'th velocity and acceleration strain vector belonging to the i 'th dashpot. The differential equations in Eq. (2) are solved numerically by discretizing time into $M + 1$ discrete points each separated by a time step $\Delta t_{n \rightarrow i+1} = t_{n+1} - t_n$, $n \in [0, M]$.

It is then assumed that the material stiffness and the damping matrices are constant in each time step. One choice could be to select the values in the middle of a time step as the constant values;

$$\widetilde{\underline{\underline{D_i}}} = \underline{\underline{D_i}}(t_{j+1/2}, T_{j+1/2}), \quad \widetilde{\underline{\underline{\eta_i}}} = \underline{\underline{\eta_i}}(t_{j+1/2}, T_{j+1/2}), \quad \widetilde{\dot{\eta}_i} = \dot{\eta}_i(t_{j+1/2}, T_{j+1/2})$$

Furthermore, the strain velocity and the strain acceleration present in Eq. (2) are assumed to, respectively, vary linearly in a time step and to be constant in time. This is formulated as

$$\dot{\epsilon}_i^d(t) = \dot{\epsilon}_{i,j}^d + \ddot{\epsilon}_{i,j \rightarrow j+1}^d (t - t_j), \quad t_j \leq t \leq t_{j+1} \quad (3)$$

$$\ddot{\epsilon}_i^d(t) = \ddot{\epsilon}_{i,j \rightarrow j+1}^d, \quad t_j \leq t \leq t_{j+1} \quad (4)$$

By integrating Eqs. (2), (4) and (5), the stress increment in each Maxwell branch in a time step is expressed as

$$\Delta \underline{\underline{\sigma}}_{i,j \rightarrow j+1} = \widetilde{\dot{\eta}_i} (\Delta t_{j \rightarrow j+1} \dot{\epsilon}_{i,j}^d + 1/2 \Delta t_{j \rightarrow j+1}^2 \ddot{\epsilon}_{i,j \rightarrow j+1}^d) + \widetilde{\underline{\underline{\eta_i}}} \Delta t_{j \rightarrow j+1} \ddot{\epsilon}_{i,j \rightarrow j+1}^d \quad (5)$$

where the constant strain acceleration vector $\ddot{\epsilon}_{i,j \rightarrow j+1}^d$ is given by the expression;

$$\ddot{\underline{\underline{\epsilon}}}_{i,j \rightarrow j+1}^d = \left[\left(\underline{\underline{\dot{\eta}}}_i + \underline{\underline{\tilde{D}}}_i \right) \Delta t_{j \rightarrow j+1}^2 / 2 + \underline{\underline{\tilde{\eta}}}_i \Delta t_{j \rightarrow j+1} \right]^{-1} \left(\underline{\underline{\tilde{D}}}_i \Delta \underline{\underline{\epsilon}} - \Delta t_{j \rightarrow j+1}^d \left(\underline{\underline{\dot{\eta}}}_i + \underline{\underline{\tilde{D}}}_i \right) \right) \quad (6)$$

The total stress increment in the Maxwell material is found by adding all stress contributions from all branches together.

$$\Delta \underline{\underline{\sigma}}_{j \rightarrow j+1} = \sum_{i=1}^N \Delta \underline{\underline{\sigma}}_{i,j \rightarrow j+1} \quad (7)$$

The strain increment vector $\Delta \underline{\underline{\epsilon}}$ is the unknown parameter iteratively changed until equilibrium is reached. This iteration process is controlled by ABAQUS when implementing the constitutive relation as a sub function into the program. The material parameters in $\underline{\underline{\tilde{D}}}_i, \underline{\underline{\tilde{\eta}}}$ and $\underline{\underline{\dot{\eta}}}$ are input parameters provided by the user.

2.2 Optimization Loop for Input Parameters

In Fig. 2 an optimization loop suggested to improve the input parameters in the ABAQUS model is visualized. It consists of an optimization algorithm, an ABAQUS simulation and DIC displacement data from a 3D print.

The purpose of the optimization loop is to minimize the difference between the DIC displacements and the ABAQUS displacements by changing the input parameters. The initial guesses for the stiffness and viscous parameters are evaluated from conventional concrete tests.

The input parameters are inserted into the ABAQUS model, which then simulates the 3D print response. Next, the displacements from the ABAQUS model and the DIC measurements from the actual 3D print are compared. The comparison represents the object function, which the optimization algorithm aims to minimize by adjusting the input parameters. The iteration loop ends when the object function is minimized.

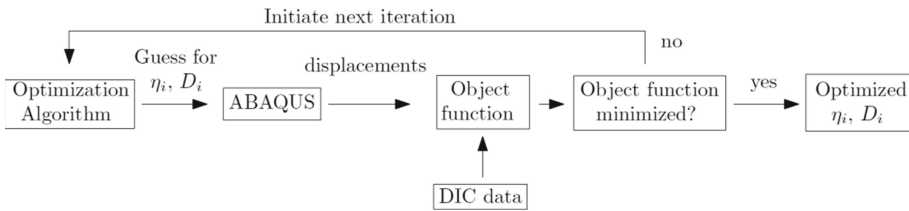


Fig. 2. Optimization loop.

2.3 Present Model Status

Currently the model suggested in the previous subsections is not fully implemented. In the current state the stiffness and damping parameters are constant with respect to time, t , and temperature, T . Furthermore, no optimization algorithm is added to the

optimization loop. Thus, the results presented in the following sections are based on a simplified (current state) version of the suggested model.

3 Materials and Methods

This section describes a 3DCP, including DIC measurements, performed at Danish Technological Institute used to exemplify the precision of the suggested numerical model.

3.1 Materials

The mortar used in the 3DCP experiments includes CEM I 52, 5 R - SR 5 (EA) white cement (Aalborg Portland), Calcium Aluminate Cement (Ternal White®), limestone filler, fine sand (maximum particle size 0.5 mm), water, and admixtures (a viscosity modifying agent, a high-range water-reducing agent and a hydration retarder). The mortar was prepared with an Eirich Intensive Mixer Type R08W.

Table 1. Mixing procedure for the base OPC-system.

Steps	Mixing time [s]
Mix dry sand and 30% water	60
Pause mixer and add the cement and limestone filler	–
Mix all material and add 60% water	120
Pause mixer and scoop material attached to the blade and pan walls	–
Add the admixtures and 10% water	–
Continue mixing	240

The mix design has a water-to-binder ratio of 0.39, 0.10% of plasticizer and 0.10% of viscosity modifying agent bwoc. Such OPC-system is then combined to a Calcium Aluminate slurry (at a binder to water ratio set at 1: 0.59) to enable sufficient structural build-up necessary to stack layers. The mixing protocol (see Table 1) comprises a 7.0 min mixing for the base OPC-system, followed by a 1.5 min mixing for the Calcium Aluminate slurry. Note that i) a resting period of 15 min is included before the slurry is added and b) the slurry is mixed in batches prior to adding the mortar to the pump.

3.2 3D Printing Experiments

The 3DCP experiments were carried out at the High-Tech Concrete Lab at the Danish Technological Institute. The 3D printing apparatus comprises a 6-axis industrial robot (FANUC R-2000iC/165F) and a progressive cavity pump (NETZSCH). The fresh mortar initially placed in a hopper is pumped into a rubber hose (3.0 m long, Ø32 mm) that is attached to a custom designed extrusion nozzle with Ø20 mm.

The experiments consisted in printing prismatic elements with a fixed geometry suggested in Suiker (2018), see Fig. 3. The print collapsed after adding layer 24.

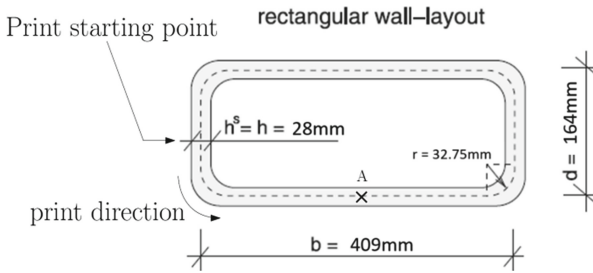


Fig. 3. 3D print geometry, from Suiker (2018).

Point A in Fig. 3 marks the point in which the DIC measurements for the optimization of the numerical input parameters are selected. The starting point of the print was in the middle of a side of length d , and with a counter clockwise printing direction. The important printing process parameters are listed in Table 2.

Table 2. Processing parameters of the printing experiments.

Process parameters	Value
Nozzle diameter, D [mm]	20.0
Nozzle height, H [mm]	10.0
Printing speed, V [mm/s]	60.0
Vertical build-up rate, V_H [m/h]	2.00
Extrusion flow rate, U [dm ³ /min]	0.89
Material density, ρ [kg/m ³]	20742
Time per layer, T_L [s]	18

3.3 Digital Image Correlation

Digital image correlation (DIC) measurements were used to measure surface displacements in a particular region of interest in the printed specimens throughout the printing process.

Two digital single-lens Canon EOS 5DS cameras (50.6 megapixel) with a macro lens (24 or 100 mm) were used to capture images of a surface of the continuously printed mortar structure. A surface picture was taken every 5 s at the same time with both cameras. Camera 1 had a 100 mm lens and the focus area of this camera was the first 12 - 14 layers of the printed structures (see Fig. 4a). The pictures started simultaneously with the printing and continued to record throughout the whole printing process. Camera 2 had a 24 mm lens and the focus area of this camera was bigger, more precisely – all front surface of the printed structure (see Fig. 4a). As Camera 1

was focused on a smaller area, more detailed measurements were expected to be possible to extract from these pictures. Additional lights were provided to the test setup making sure that a high quality images could be captured of the printed surface, see Fig. 4b.

Afterwards, the images were post-processed using commercially available DIC software GOM Correlate. The post processing allowed to measure the full field surface displacements of the focused area that occurred while the printing of the structure was continued.

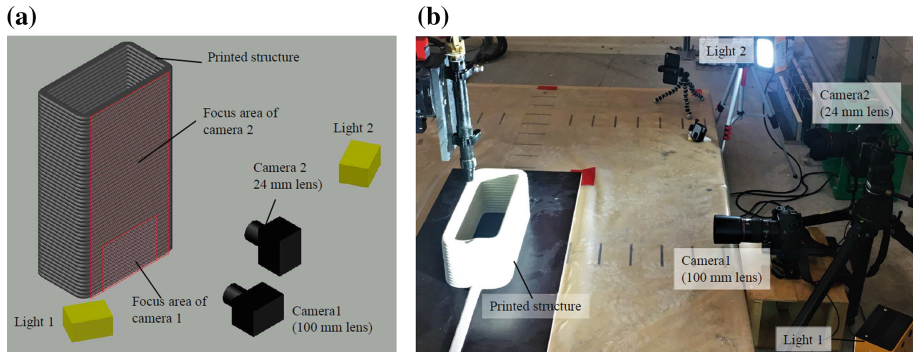


Fig. 4. Test setup for DIC measurements: (a) sketch of the setup with highlighted measurement (focus) areas for each camera; (b) photo of actual setup.

4 Numerical Model Validation

The suggested numerical model used to predict the response of the 3D prints is presented. Furthermore, the results of the model predictions are presented and discussed.

4.1 ABAQUS Model

In order to minimize the computational time only the straight wall of length b in Fig. 3 is modelled in ABAQUS. The ends of the wall are restricted against movement in the printing direction (x -direction), see Fig. 5. Furthermore, the bottom of the first print layer is restricted against translations in all directions. A six-noded wedge element with linear interpolation and full integration, denoted C3D6, is used for the meshing.

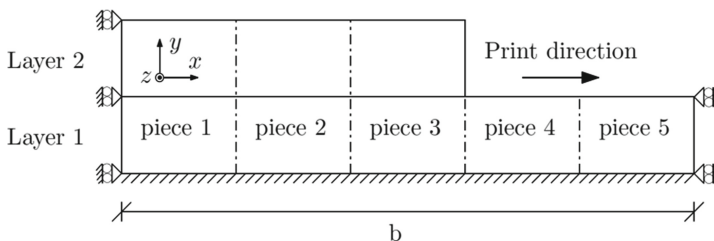


Fig. 5. Sketch of boundary conditions and print ‘pieces’ in 3D print simulations.

The model divides the wall in five ‘pieces’ of equal length, see Fig. 5. Each ‘piece’ is added one at a time separated by a time interval corresponding to printing the piece. The applied constitutive model contains a single Maxwell branch, i.e. one spring stiffness and one dashpot in series. Both of the values are constant in the given case.

4.2 Optimization of Input Parameters

For the optimization process, the distance increment $\Delta u(t-t_0)$ between the center of layer 1 and layer 2 in point A (cf. Fig. 3) is considered. This is sketched in Fig. 6, where t_0 refers to the point in time where the comparison between the DIC measurements and ABAQUS simulation results is started. In the given case the comparison is started when the print of layer four is initiated, i.e. $t_0 = 3T_L$. As stated previously, the optimization loop has not been implemented yet. Thus, the fitting of the input parameters is done manually.

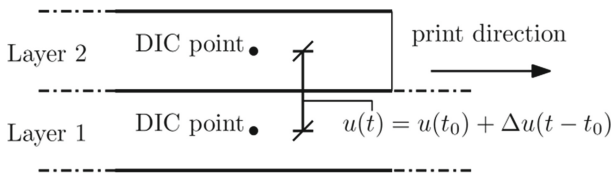


Fig. 6. Distance between the center points of layer 1 and layer 2.

In Table 3 the parameters found from the fit are listed. It was selected to fit the parameters to the DIC measurements in the interval where layer four to six were printed. The initial value of the D_1 was taken as $1e5$ Pa, which corresponds to the order of magnitude measured from a rheometry test of the print material following the principles in Leal da Silva (2020).

Table 3. Fitted input parameters for ABAQUS model.

Input parameters	Value
D_1 [Pa]	$3e4$
η_1 [Pa·s]	$1e8$

In Fig. 7 the distance increments from the DIC measurements and the ABAQUS simulations including the parameters in Table 3 are shown. The vertical axis represents displacements and the horizontal axis represent time divided by T_L (which corresponds to number of printed layers). The timeline is started when printing of the fourth layer is initiated.

From Fig. 7 it is seen that the DIC displacements and the ABAQUS displacements are in the same order of magnitude. A significant decrease in $\Delta u(t-t_0)$ occurs in the DIC measurements during the printing of the fourth layer. However, when the following

layers are added, only minor changes are seen. Thus, the material stiffness seems to increase significantly after compaction.

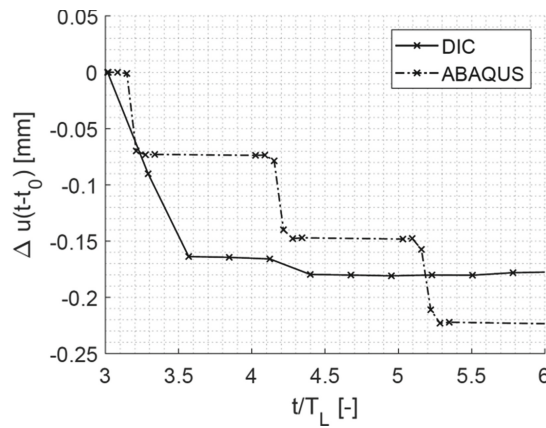


Fig. 7. Distance increment $\Delta u(t - t_0)$ based on DIC measurements and ABAQUS simulations, with $t_0 = 3T_L$

The ABAQUS displacements, on the other hand, are seen decrease by the same order of magnitude every time a new layer is added directly on top of point A considered for the optimization ($t/T_L \approx 3.25, 4.25, 5.25$). This is expected, since the constitutive model contains a constant spring parameter, which does not take curing of the material into account. The most significant decreases in the DIC measurements takes place around $t/T_L \approx 3.25, 3.5$, i.e. immediately when loading is added directly on top of point A and shortly after.

4.3 Model Verification and Discussion

As previously reported, the 3D print collapsed in the wall part of length b after stacking 24 layers, see Fig. 8. By use of the optimized parameters in Table 3 ABAQUS predicted a collapse at 10, layers. This corresponds to a deviation of 58% compared to the actual 3D print observations.

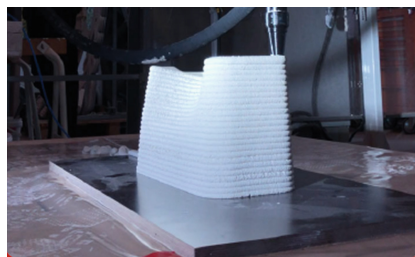


Fig. 8. Collapse of 3D print at Danish Technological Institute (24 layers).

The significant deviation was, however, expected, since the numerical model applied is very simple. First of all only one set of (constant) input parameters are used. Furthermore, they only fitted to match the interval where layer four to six are printed (cf. Fig. 7). A significant improvement in the ABAQUS modelling of the 3D print is expected when the input parameters become a function of time and temperature. This will e.g. allow the model to include aging effects in the material.

5 Conclusion

An improved numerical model to simulate 3DCP was suggested. It consisted of an ABAQUS model including an incremental constitutive equation describing a viscous material and an optimization loop used to improve the model input parameters by use of DIC measurements. Currently the suggested model is only partly implemented. A simplified model was, therefore, used to illustrate the principles of the suggested model. An ABAQUS model including a single Maxwell branch with constant stiffness and damping parameters predicted the collapse of an actual 3D print at 10 layers. This corresponded to a relative error of 58% compared to the actual print observations which was concluded to be a significant deviation, but also to be expected due to the simplified (current state) model used. Finally it was argued that future versions of the model are expected to improve the prediction of the 3D print behavior.

Acknowledgements. The authors would like to acknowledge the support of the Innovation Fund Denmark (Grant no. 8055-00030B: Next Generation of 3D-printed Concrete Structures).

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Characterisation of the Layer Pressing Strategy for Concrete 3D Printing

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Abstract. 3d printing of cementitious material by pressing layers during the extrusion is a strategy that requires a rather low initial yield stress so the material can deform without cracking. It allows to perfectly control the height of the layer and gives freedom in the orientation of the printing head and of the layer allowing for a wider range of printable geometry than the classic so-called “infinite brick” extrusion. This strategy has however some drawbacks as pressing the material on the previous layers may lead to a deformation of the sub-layers and even failure of the structure. In this work; we make a first step into understanding forces involved in such a process and measure their dependency on material fresh properties and printing parameters.

Keywords: 3d concrete printing · Yield stress · Layer pressing · Printing parameters · Geometry control

1 Introduction

The development of 3d printing of cementitious materials has led to multiple solutions or strategies for extruding layers, each one opening new paths for research and development [1]. Figure 1 illustrates in an asymptotic way these strategies at the level of the nozzle. The infinite brick extrusion consists in extruding unsheared material through a nozzle that imposes its shape to the layer. The simplicity of this process is balanced by the limitations in terms of achievable global shapes (i.e. layers can only be stacked vertically) and control over the layer geometry (i.e. in-line monitoring of the geometry may prove necessary due to error accumulation [2]). The free flow deposition lacks any control over the layer geometry, only the volume of extruded material is known and the final shape results from a complex competition between gravity and thixotropy [3]. An example of application of this strategy is developed in [4].

The third strategy consists in pressing the layers during the extrusion so that the height of the layer is always imposed by the relative position of the nozzle. The material is then free to deform between the substrate (or the previous layer) and the nozzle giving to this process the freedom to allow for a potential

inclination of the printing head and, in turn, of the printed layer [5] (note that curved layer can be printed without inclining the extrusion head [6], but the generation of the toolpath becomes difficult). It moreover allows for variations in the layer cross section during a print by playing on one of the printing parameters involved, namely the printing speed V_r , the extrusion speed V_e or the extrusion height H .

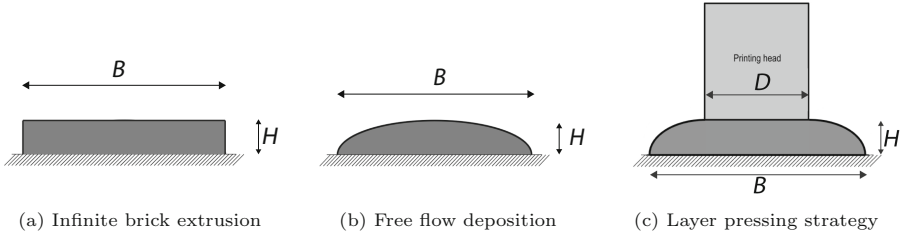


Fig. 1. Different extrusion strategies for 3d printing at the nozzle

The drawbacks with the such a printing strategy is that while pressing the layers, an additional force is applied on the previously printed layers. If the induced stress exceeds the yield stress of the material, this may lead to periodic deformations shown in Fig. 2, *left* or even to a global failure of the object (Fig. 2, *right*).

Within this frame, the goal of the present paper is to assess the magnitude of this additional force occurring locally during the extrusion, and inform the design and fabrication processes with it.

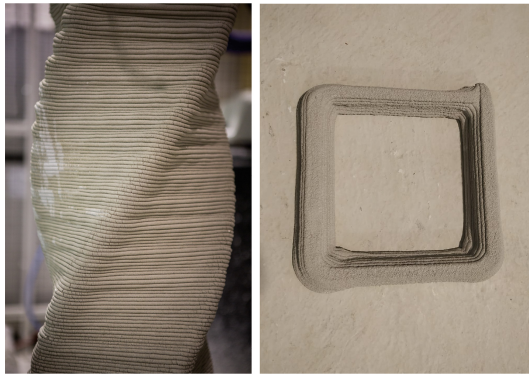


Fig. 2. *left*: wave pattern on a column appearing during printing (photo credits: Stefano Borghi), *right*: plastic collapse on a 10 layers piece due to the extra force applied on substrate during the extrusion (photo credits: Paul Carneau).

1.1 Method Statement

In a first part, we focus on the geometric characterisation of a layer which is pressed by the nozzle on the substrate. Our results illustrates how the layer's section is different from the nozzle geometry due to the material deformation through the extrusion/deposition process. In a second part we develop an experimental protocol allowing for the measurement of the additional force induced by the pressing of the extruded layers. Finally, we discuss the results obtained by the experiment in regards to layer geometry and material properties.

2 Geometric Characterisation of the Layer's Section

The layer pressing strategy relies on kinematic parameters, geometrical parameters and material parameters, all of which are listed in Table 1. In the following, we consider a Bingham fluid, with yield stress τ_c and plastic viscosity ν . The proposed model could however be extended to more complex models for yield stress fluids.

The process of pressing layers is characterised by a fluid extruded at a velocity V_e through a nozzle of diameter D and height H , by a robot moving at a speed V_r . The result is a layer of width B (independent of the nozzle diameter D) and whose height H is directly given by the height of the nozzle.

Table 1. 3d printing process parameters: bold values can be independently controlled.

Parameter	Symbol	Unit	Category
Robot speed	V_r	m.s^{-1}	kinematic
Extrusion speed	V_e	m.s^{-1}	
Height of layer	H	m	Geometric
Width of layer	B	m	
Nozzle diameter	D	m	
Yield stress	τ_c	Pa	Material
Dynamic viscosity	μ	Pa.s	

This section studies the kinematic and geometric parameters of the printing process. The goal is to determine the parameter range allowing to control the layer's geometry for the experimental validation, which is presented in the next section.

2.1 Lace Stretching

If we consider that the nozzle diameter D stays unchanged through the printing process, we can introduce the nozzle section as $dS = \pi D^2/4$. We call dS' the

cross section of a layer, which can vary continuously during a print by changing any of the control parameters (robot speed V_r , flow rate V_e or height H). The ratio dS/dS' between initial and final material cross section provides information on the imposed strain and therefore on the longitudinal stresses in the layer. Indeed, if the final cross section is larger than the nozzle cross section, the layer is compressed. If this ratio is smaller than one, the material undergoes a striction and the layer is extruded with a longitudinal tensile stress which can lead to cracks or discontinuity as shown in Fig. 3. In [7], a study of printing parameters impacting the cracking is conducted in order to voluntarily create weak parts in an object that can easily be removed afterwards.

The conservation of mass implies that $V_e dS = V_r dS'$. The above section ratio can therefore be rewritten as a ratio between velocities, which are the printing parameters that are the relevant parameters used in practice. In the following, we will target a ratio V_r/V_e around 1 to avoid the generation of any longitudinal stresses and isolate the vertical consequences of pressing layers.



Fig. 3. Longitudinal tearing in the extruded material creating discontinuous layers (photo credits: Paul Carneau)

2.2 Shape of the Layer Profile After Pressing

The first objective is to estimate the shape of the deformed layer after pressing. Indeed, the width B cannot directly be controlled by the printing operator, but rather indirectly imposed by controlling the other printing parameters. The layer pressing strategy offers the freedom to modify parameters during the printing process to modify the geometry of the layer that can fit design requirements (like for example having thicker wall at the base than at the top). The counterpart is the necessity for the user to understand and calibrate the indirect impact of each control parameter on the resulting layer cross section.

Using the fact that $dS = \pi D^2/4$, and introducing a shape parameter β so that $dS' = \beta BH$, we have:

$$\frac{\pi D^2}{4BH} = \beta \frac{V_r}{V_e} \quad (1)$$

β describes the discrepancy between the real section of the layer and a ideal rectangular section of width B and height H as illustrated in Fig. 4. We have thus for example $\beta = 1$ for a rectangular section and $\beta = \pi/4$ for an elliptical profile.

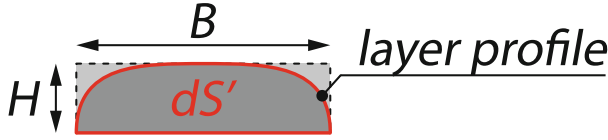


Fig. 4. Real layer profile compared to an ideal rectangular section of area HB

2.3 Kinematic Conditions for Pressing Layers

As mentioned above, the main interest in pressing the layers is the capacity to control the height of the layer and, in case of deformation of the layers below, to recover from such discrepancies by ensuring that the height of the layer equals the distance between the nozzle and the substrate.

To achieve this, the first condition is related to the material properties as the layer has to withstand its own weight [8,9]:

$$\frac{\rho g H}{\sqrt{3}} \leq \tau_0 \quad (2)$$

The second condition is purely kinematic and it has previously been identified for viscoelastic material [10]. Let us consider a part of a layer of length D that has just been extruded at a velocity V_r . The time to extrude this volume of material is obviously $t_c = \frac{D}{V_r}$. This characteristic time is the duration the robot spends above a specific section of the layer.

Before being extruded, this volume of material was a cylinder of diameter D and height $L_c = V_e \times t_c = \frac{DV_e}{V_r}$ inside the extrusion head. A straightforward condition for pressing the layer, illustrated in Fig. 5 can be set as the height of the cylinder inside the nozzle L_c must be larger than the distance H between the nozzle and the sub-layers. This condition reads:

$$H < \frac{DV_e}{V_r} \quad (3)$$

3 Experimental Study of Vertical Loading

The above considerations can only be valid if a pressure force due to the extrusion process and independent from the material weight actually exist. The following experiment aims at measuring for the first time this additional force and assess its amplitude and comparing it to the layers weight.

In the experimental set-up, the robot extrudes layers directly onto a scale which measures thus the cumulative weight of the laces along with the force F due to pressing. Each series of test is composed of 5 laces, the robot following the toolpath shown in Fig. 6. The plate surrounding the scale allows to keep the pressure in the extrusion head even when not above the scale in order to eliminate variation in the measures coming from a refilling of the tube at the

start of each new lace. The layers are printed in decreasing height order (from larger H to smaller).

The composition of the material used for this experiment is detailed in Table 2 for information. Indeed the equations introduced in this article involving stresses are valid for any yield stress material and the geometric and kinematic conditions are valid for any incompressible fluid.

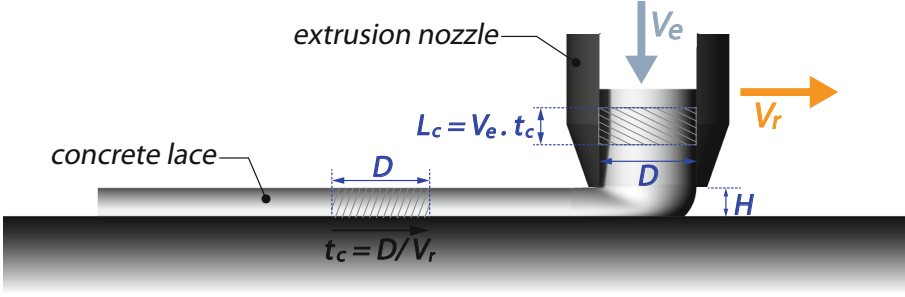


Fig. 5. The layer is pressed if the height L_c is larger than the final height H .



Fig. 6. *left:* Experimental apparatus with a scale and surrounded plate, and toolpath to measure the force applied during the extrusion, *right:* On-going printing of the layers on the scale (photo credits: Romain Mesnil).

The yield stress of the material is determined before each series using the protocol described in [11]. Table 3 below shows the parameters used for each series of tests.

The printing velocity and flow rate are imposed by the manipulator directly to the robot and the dosing pump equipped on the extrusion head. Although the robot accuracy is reliable, it can be verified by dividing the toolpath length by the deposition time measured on Fig. 7.

The width of the layers B is measured physically just after extrusion. Figure 7 shows the weight measured by the scale as a function of time for each of the three

series of tests. On each curve, the five different paths can be identified, the overall slope giving the exact flow rate achieved during the experiment. This exact flow rate can differ from the value imposed to the pump and is thus preferred for the rest of the calculations.

Table 2. Premix composition

Components	Mass ratio
Portland cement CEM I	30–40%
Crystalline Silica	40–50%
Silica fume	10%
Limestone filler	10%
Water/powder ratio	0.1

The additional force F to measure can be identified from the graph as the jump between the horizontal plateau and the linear part of the curve for each layer. It can be noted at this stage, that this jump increases as the layer height H decreases.

To measure this force precisely, we subtract the self-weight of the material to the total measurement. This way, we ensure that F does not include the weight of the material.

Table 3. Experimental parameters and results

Serie		A					B					C				
Parameter	Unit	1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
Density	-	2484					2512					2512				
Yield stress	Pa	500					200					200				
Nozzle diameter D	mm	20					20					20				
Velocity V_r	mm/s	41.5					55.4					41.5				
Flow rate	g/s	33.7					40					18.6				
Height H	mm	20	15.7	12	10	8	20	15.7	12	10	8	20	15.7	12	10	8

4 Results and Discussions

4.1 Layer Geometry Control

The first result concerns the geometry control of a layer. Figure 8 gives coefficient $\beta = dS'/BH$ as a function of the target height of the layer H . For smaller values of H , β shows a plateau whose length is linked to the yield stress of the material

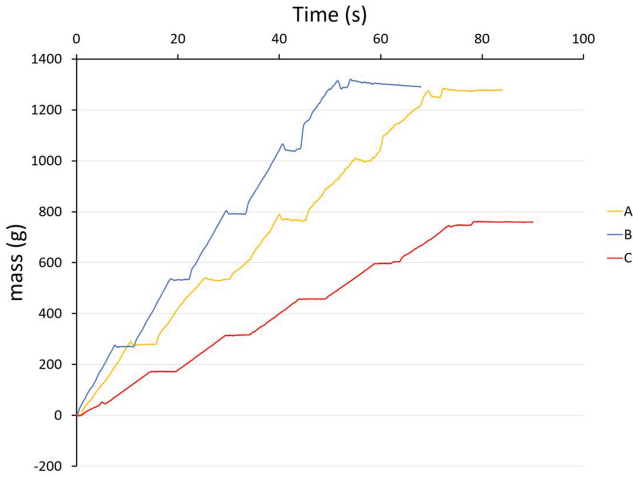


Fig. 7. Mass measured by the scale in function of the time for the three series of test.

τ_0 . Then when the height increases, β decreases with a constant slope. This part corresponds to layers printed without any exact control over the geometry. The final height of the layers is different from the target height H due to an uncontrolled flow of the material under a combination of its own weight and of the force applied during the extrusion.

In the case where the robot speed and the extrusion velocity are of the same magnitude (series A and B) the value $\beta = 0.8$ provides a good evaluation of the exact layer cross section.

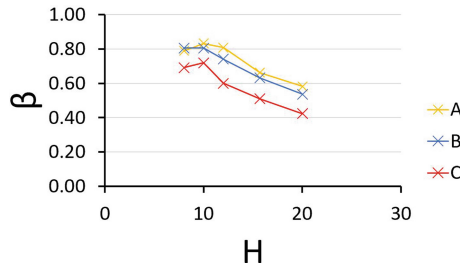


Fig. 8. Coefficient β for the different series of experiment. β reflects the geometry control of the layer.

4.2 Self-weight and Applied Force

In this section we compare the stress induced by the self-weight of the layer w and the stress coming from the extrusion and pressing process τ_e only:

$$\begin{cases} w = \frac{\rho g H}{\sqrt{3}} \\ \tau_e = \frac{4F}{\pi D^2} \end{cases} \quad (4)$$

The results are presented in Fig. 9 for each three series of experience. As expected, w evolves linearly with H while τ_e seems to be inversely proportional to it. Therefore, as H decreases, the force due to the extrusion becomes preponderant over the material self-weight.

In the case of the infinite brick extrusion strategy, where all stresses come down to the weight of the material only, Kruger et al. have developed a model [12] to optimise printing parameters. With the layer pressing strategy, such a model shall be completed by accounting for the contribution of the stresses coming from the pressing force and its influence on the failure modes [13].

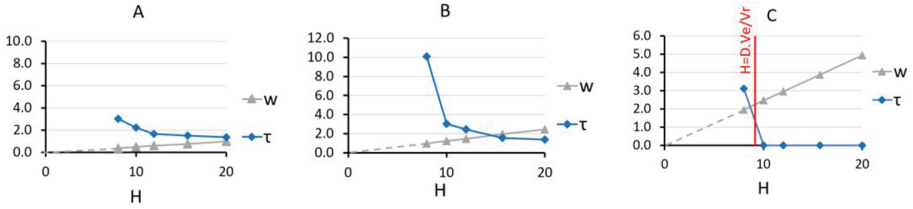


Fig. 9. Comparison of non-dimensional stresses w^* and τ^* for the three series of tests

Looking at the results of serie C in Fig. 9, it appears that no force was measured by the scale other than the one coming from the self-weight. This can be explained by drawing the layer pressing criteria described earlier $H < \frac{DV_e}{V_r}$ on the graph (see the red line). It separates exactly the laces where an additional force was measured from the laces that were simply deposited. This seems to validate our layer pressing condition as a good first evaluation of the parameters toward a better control of the layer geometry. In addition, by observing that $\frac{DV_e}{V_r} \propto \frac{Q}{DV_r}$, the user can ensure the condition is fulfilled by simply changing the nozzle diameter, without impacting the layer geometry.

Finally, to give a better understanding of the amplitude of the pressing force compare to the weight of the material, we plot in Fig. 10 the ratio between the pressing force and the weight of one layer τ_e/w as a function of the height of the layers. The Y-axis corresponds therefore to the number of layers whose total weight is equivalent to the pressing force acting on the substrate.

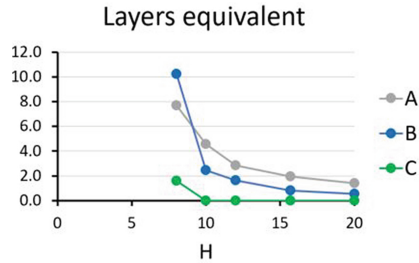


Fig. 10. Pressing force expressed in terms of number of layers of equivalent height H .

5 Conclusion

The layer pressing strategy for 3d printing of cementitious material offers interesting perspectives in terms of achievable geometries and innovative printing strategies. However the additional force induced by the pressing of the extruded material on the sub-layers may lead to a local failure of the sub-layers independently of the weight of the material. The experience described in this paper highlights first the impact of the measured force on the control of the layer section geometry. It then compares it to the self-weight of the material to justify the importance of taking it into account when choosing the printing parameters.

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A Compendious Rheo-Mechanical Test for Printability Assessment of 3D Printable Concrete

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Abstract. A successful 3D concrete print (3DCP) is controlled by a sound buildability and good pumpability. Since both factors rely on the behavior of concrete in the fresh state, rheological assessment is crucial prior to 3DCP. In a previous study done by Roussel [1], a correlation of numerical simulation of ASTM mini-slump cone flow and rheometer results was successfully addressed. As the model solely considers material flow under gravitational loading, this model can be adjusted with an external source of energy in the form of impact loading by vertical drop from a certain height to emulate the agitation and deposition process of 3DCP. A flow table and rheometer tests were executed with 5 samples of different consistency. Consecutively, 3DCP validation was performed except for the sample with no superplasticizer content. The study shows the relative deformation (%) varied in a range of 34% - 89% after the drops according to the consistency of the sample. The initial static and dynamic yield stresses are also presented in a range of 0.94–6.82 kPa and 0.54–4.73 kPa respectively. Based on the results, flow table reading ranges are suggested for suitable 3D printability.

Keywords: 3D concrete printing · Rheo-Mechanics · Printability test method · Mini-slump cone · Buildability · Rheology

1 Introduction

The quality of an extrusion and layer depository based digital construction, so-called 3D concrete print (3DCP), is influenced by several factors, e.g. printing parameters, the geometry of printed object, and rheological properties of the material in the fresh state. Buildability, extrudability and pumpability are the terms to describe the printability or quality of the 3D printing. To manipulate the printability, the rheology of material is the dominant variant while the others are normally considered as prescribed factors. Hence, the correctly measured rheological measurement data is significantly important to design 3D printable concrete material.

Sophisticated rheological measurement devices, known as rheometers, are customarily employed to characterise rheological behaviour due to its comprehensiveness.

From the results the static and dynamic yield shear stresses are plotted to attain thixotropic parameters, which are among the principal factors to determine printability of the material [2, 3]. Due to the rather lengthy process and intricate procedure, the rheological characterisation is commonly performed on separate batches of concrete before commencing with the 3D printing process. Due to the complex process as well as the high-cost measurement devices, it is mainly used in a laboratory environment. A further complication is variability in rheology properties in different batches despite care for reproducibility [4].

Despite the existing compact test methods for measuring specific yield stress, e.g. continuous penetration test [5], there is a possibility to adapt the ASTM mini-slump cone test [6] for 3D printing because it is relatively quick and simple, but comprehensive. Roussel et al. [7] developed a numerical model for the ASTM mini-slump cone flow when the mold is solely lifted. Here it is proposed to evaluate printability by including a mechanical impact loading caused by dropping the top plate by a certain height. The impact loading may simulate the agitation induced by pumping and transport of the concrete before extrusion during 3DCP. Consequently, an indication of microstructural breakdown resulting in the reduced dynamic yield shear stress can be obtained, by which pumpability and buildability could be estimated concurrently.

This is a preliminary experimental study to investigate the correlation between rheological measurements obtained by a rheometer and the spread diameter from flow table testing after applying impact loadings.

2 Experimental Methods and Program

2.1 Mix Design and Test Set Configuration

A suitable mix design for 3DCP, given in Table 1, has been developed with locally sourced materials and optimised in previous studies [8], consequently forming the reference mix (S_1SP) for this research.

Table 1. 3D printable concrete mix composition.

Constituent	Description	RD	Mass [kg]
Cement	PPC SureTech 52.5 N	3.14	579
Fly ash	DuraPozz Class F	2.2	165
Silica fume	SiliconSmelters MicroFume	2.1	83
Fine aggregate	Local Malmesbury (4.75 mm max. size)	2.65	1167
Water	Potable Tap Water	1	261
SP	Chryso Premia 310	1.05	5.0

In order to characterise the behaviour of fresh concrete under impact loading on a flow table, the consistency of fresh concrete was differentiated into 5 test sets with altered polycarboxylate polymer-based superplasticizer (SP) contents. From the reference or Standard sample mix (S_1SP), two low consistency samples were prepared with a superplasticizer content reduction by 50% and 100%, namely S_0.5SP and

S_0SP respectively, while the other samples contain increased superplasticizer by 50% and 100%, namely S_1.5SP and S_2SP respectively, to achieve a high consistency (see Table 2). On average, the density of freshly mixed concrete mixture is 2100 kg/m³.

Table 2. Test set configurations.

	S_0SP	S_0.5SP	S_1SP	S_1.5SP	S_2SP
SP contents [kg/m ³]	0 (−100%)	2.5 (−50%)	5 (+0%)	7.5 (+50%)	10 (+100%)

2.2 Slump Cone Flow Table Test

As specified in ASTM C230/230 M, the standardised flow table apparatus was prepared with the presence of recording cameras in three orthogonal directions (i.e. x- (front), z- (side), and y- (top) directions), as shown in Fig. 1.a.

A smooth finished conical bronze or brass mould (50 mm high, top diameter 70 mm and bottom diameter 100 mm) is first placed on the mounted circular rigid flow table with a finely machined plane surface free of defects (255 mm diameter and 4.08 kg mass). Once the mould is filled with a freshly prepared concrete mixture, the mould is gently lifted without a remarkable disturbance. An impact loading is transmitted to the mixture caused by the collision of the top flow table to the bottom stand as it drops through a constant height of 12.7 mm for 15 times at a constant rate (See Fig. 1.a). A frictional intervention between the mould and flow table surface is assumed to be negligible since the contact surface of both apparatuses is smoothly machined.

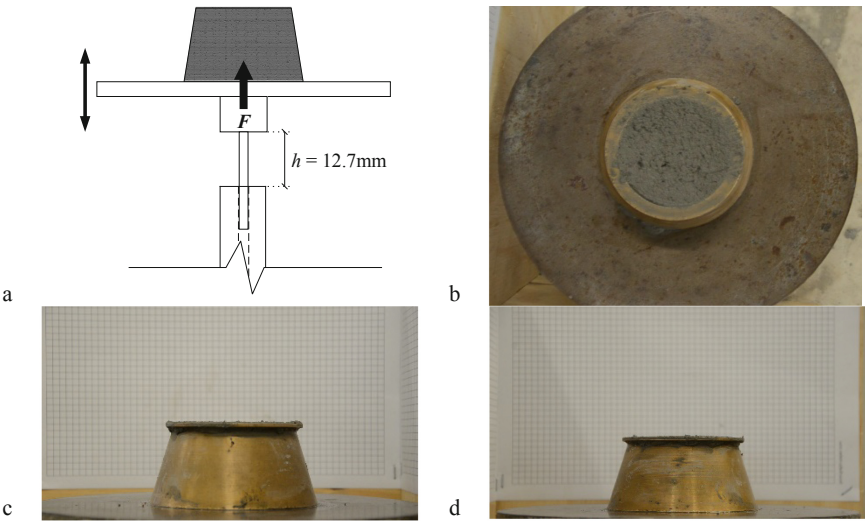


Fig. 1. a. A brief illustration of the impact loading caused by flow table test; b. real setup of slump cone of top view for calibration purpose (along the y-axis); c. front view (along x-axis); d. side view (along the z-axis).

Stress induced by applied loading, i.e. self-weight and impact, is depicted as a horizontal line and labelled as C in Fig. 2. The line-C moves downwards when the specimen surface contact area with flow table increases as it spreads, and it moves upwards when impact loading is applied. In other words, deformation starts when the line-C exceeds the shear capacity of a material, until a state of equilibrium is reached again.

The initial deformation (d_0) is solely influenced under the gravitational loading from the density of the concrete mixture when the mould is lifted with no agitation action. Since the material is not disturbed or agitated, the flow onset of d_0 only occurs when line-C by gravitational load exceeds the material's initial static shear capacity (line-A in Fig. 2). The initial deformation ceases when a state of equilibrium is reached, which can also be described as material shape retention.

Likewise, plastic deformation begins when the line-C by first impact loading exceeds line-A. However, the shear stress-responsive curve may be subsided down due to the structural breakdown of material which was displayed as a deformation. Subsequently, the subsided shear static capacity (line-B) becomes the verge for flow onset.

Because the relatively constant time gap between the vertical drops does not allow enough time for significant structural buildup, the line-B is assumed to remain constant.

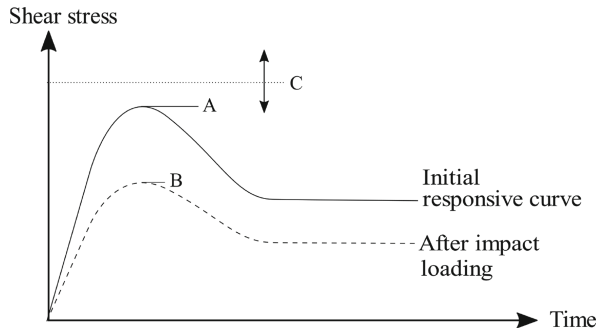


Fig. 2. An illustration of flow onset of a thixotropic concrete mixture, which depends on the loading and material behavior in fresh states.

The average flow diameter of the mixture is then digitally recorded by means of video footage. In processing the digitally recorded image data, the scale is calibrated with the outer diameter of the bronze mould, 105 mm with 5 mm thickness of the mould, for all directions and test sets. Based on the calibration, the relative displacement [%] can be recorded at every drop.

2.3 Rheometer Measurement

The empirical and indicative correlation of rheological parameters with slump flow diameter is the main objective of this paper. Thus, a precise measurement device is required, here a rheometer, to obtain the rheological parameters (static yield stress, τ_s ; dynamic yield stress, τ_d ; structuration rate, A_{thix} [2] and re-flocculation rate, R_{thix} [3]).

A rotational cylinder type rheometer, RHM-3005/3009, produced by the Germann Instruments ICAR (International Center for Aggregate Research) was used to investigate the rheological parameters. A stress growth test, determining static and dynamic yield stress of the mixture, at 1.0 s^{-1} shear rate was performed at various resting periods, up to 300 s, for time-dependent thixotropic parameters determination. However, it is noted that the test setup with a relatively short resting time frame, designed to emulate the quick nature of the flow table test, does not showcase the long-term thixotropic parameter, the structuration rate, A_{thix} , i.e. no distinct structuration behaviour was shown within 300 s.

2.4 3D printing validation

Once the rheological characterisation process was finished for all test sets, circular column samples were 3D printed with the five different fresh materials as validation. The currently available 3D printer has a 1 m^3 build volume and 25 mm diameter nozzle at three translational degrees of freedom [9].

As the validation is to check the printability performance, i.e. buildability and pumpability, during a sole period of printing, an analytical buildability model presented by Kruger et al. [8] was employed while the pumpability can be checked with a presence of discontinuity of printing filament. The model predicts the number of buildable filament layers during the 3D printing until it fails by plastic yielding failure mechanism which occurs either: 1) during re-flocculation for a fast vertical building rate or 2) during structuration for a normal or slow vertical building rate (see Fig. 3). The buildability model includes the 3D print parameters presented in Table 3 for the selected 250 mm diameter circular hollow column. 3D printing continues until global failure occurs.

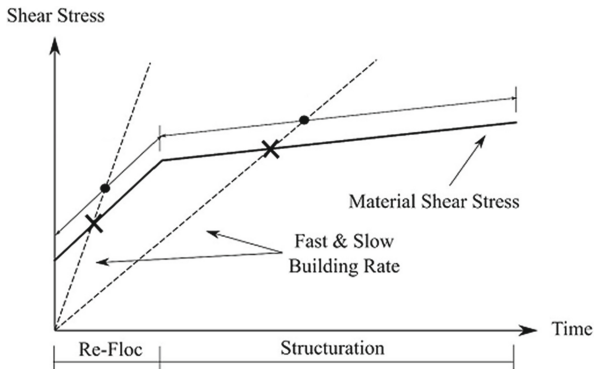


Fig. 3. A time-dependent bi-linear thixotropic model [3] with example building rates. Plastic yielding failure occurs during either re-flocculation or structuration phases depends on the building rate [8].

Table 3. Input parameters for buildability model prediction.

Parameters	Layer height (h)	Layer width (w)	Path length per layer (l)	Printing speed (v)	Aspects ratio (h/w)
Value	10 mm	30 mm	785 mm	60 mm/s	0.33

3 Results

3.1 Slump Cone Flow Table Test

The mean value of flow diameter or relative deformation to the 100 mm undeformed diameter in each test set was calculated by recorded digital images in three directions.

The mean flow diameters at each vertical drop ($d_1, \dots, d_{15}$) for all test sets are plotted in Fig. 4. Only S_2SP displayed a notable initial deformation (d_0) under self-weight loading. Each of S_0SP, S_0.5SP and S_1SP shows its own distinctive deformation profile and approximately linear increments while S_1.5SP and S_2SP result in a similar profile. In other words, the superplasticizer overdosage passes a saturation point in a concrete mixture. Thus, the saturated concrete mixture yields a similar flow response under the loadings even if the dosage is not the same.

Table 4 presents the initial deformation and the final deformation after 15 vertical drops. The correlation between the result and the rheological parameter will be discussed in the following section.

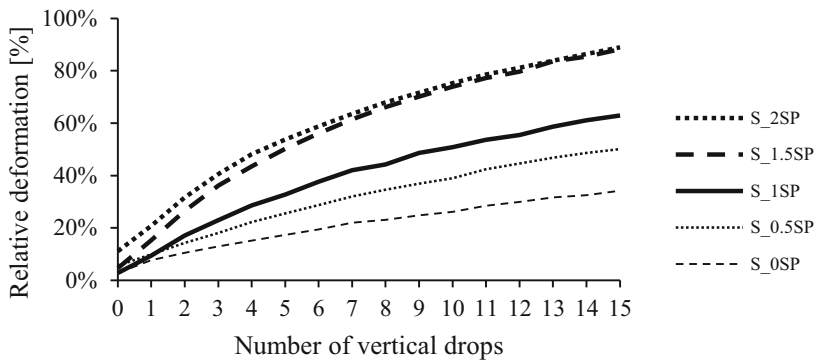


Fig. 4. Relative deformation in percentage at each vertical drop for all test sets.

Table 4. Initial and final mean flow diameter (units are in mm).

	S_0SP	S_0.5SP	S_1SP	S_1.5SP	S_2SP
d_0	102.79	105.61	102.76	104.61	111.15
d_{15}	134.25	150.09	162.90	188.27	188.97
Difference (%)	30.6%	42.1%	58.5%	80.0%	70.0%

3.2 Rheometer Measurement

The initial rheological parameters are crucial to predict the buildability and pumpability. Initial stress growth rheometer test results of all test sets are shown in Fig. 5.a with static and dynamic yield stress values. Considerable static and dynamic yield stress increases are found in the test sets with reduction of superplasticizer content, i.e. S_0SP and S_0.5SP. On the other hand, the control sample, S_1SP, exhibits a similar rheological response to S_1.5SP.

The re-flocculation rate (R_{thix}) calculation plot for the control sample is presented in Fig. 5.b. The graph shows a rapid restoration of its flocculation structure after the initial dynamic yield stress which emulates the agitation process. It is a typical response of thixotropic material where it also displays the best fitting in the graph.

The calculated re-flocculation rate and initial shear yield stress values are summarised in Table 5 as inputs for the buildability prediction model.

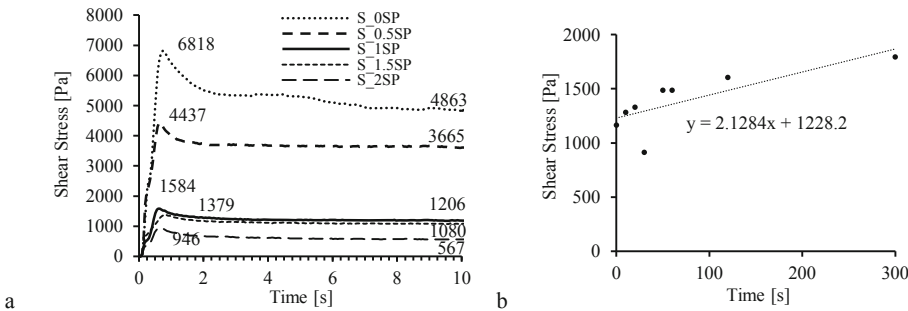


Fig. 5. a. Initial stress growth rheometer test results; b. Calculation of the re-flocculation (R_{thix}) rate of S_1SP.

Table 5. Summarised rheological parameters.

	S_0SP	S_0.5SP	S_1SP	S_1.5SP	S_2SP
τ_s [Pa]	6818	4437	1584	1379	946
τ_d [Pa]	4863	3665	1206	1080	567
R_{thix} [Pa/s]	1.47	1.69	2.13	0.42	0.68

3.3 3D printing validation

The images in Fig. 6 depict the successfully 3D printed column just before the onset of global failure for all samples, i.e. S_0.5SP, ..., S_2SP. As S_0SP exhibited excessively stiff behavior in a fresh state, it was considered not to print with no external agitation energy source, e.g. poker vibrator, due to the possibility of damage in a pump or delivery pipe.

It is noted that a slight stoppage at layer 10 and 20 was found during the printing process for unknown reasons. The lagging motion created an excessive deposit at the point. This phenomenon is discussed in the next section.

Table 6 shows the predicted maximum number of layers for the 3D printed object and the recorded number of layers during the validation process. It is found that none of the validation results exceeds the prediction even though most of the results fall in a reasonable range. Although S_0.5SP recorded the highest number of printed layers, it resulted in the intolerable error to the buildability model prediction. This discrepancy which results in a relatively low number of printed layers despite the high static yield stress will be further investigated.

Table 6. Number of printed layers without a major deformation or global failure (governing thixotropic parameter is specified in the bracket).

	S_0SP	S_0.5SP	S_1SP	S_1.5SP	S_2SP
Predicted layers	113 (A_{thix})	78 (A_{thix})	28 (A_{thix})	20 (R_{thix})	11 (R_{thix})
Validated layers	–	33	26	20	9
Error %	–	–58%	–7%	0%	–18%

With no discontinuity of material delivery from pump to nozzle in printing process for all test sets, S_0.5SP (Fig. 6.a) and S_1SP (Fig. 6.b) exhibit sound buildability while the other two (Fig. 6.c and 6.d) shows a notable local deformation of each filament, consequently it leads layers to be wobbled and exhibit a global deformation of the structure. In aspects of surface finish quality, S_0.5SP shows poor surface finishing in the form of surface rupture due to the low superplasticizer content.

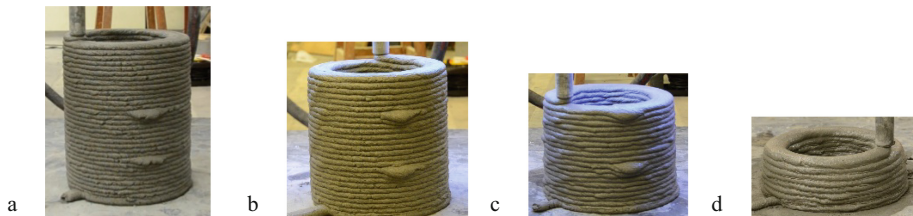


Fig. 6. 3D printing validation of all test sets, except S_0SP which is considered not to be pumpable. a. S_0.5SP; b. S_1SP; c. S_1.5SP and d. S_2SP.

4 Discussion

This experimental study is a preliminary feasibility study for the development of an adjusted analytical model for flow table testing with impact loadings. Since the vertical impact loading of the flow table is a different form of agitation than the rotational agitation of rheometer, a strong correlation is not expected. The small number of

samples together with substantial superplasticizer dosage differences in samples also do not justify a strong conclusion. However, it is worthwhile to find that the repetitive dynamic loading to the material successfully emulates the structural breakdown of the material.

A bi-linear relationship of shear yield capacity over superplasticizer dosage is found. A high rate of shear stress reduction is expected before the saturation point, then the rate flattens out. Likewise, slump flow table results also exhibit a bi-linear relationship (see Fig. 7.a). Even though the intersection bi-linear in two graphs slightly differ, it can be postulated an exact saturation point is in between S_1SP and S_1.5SP.

During the 3D printing process, the percentage of error was relatively small except S_0.5SP which resulted in a significantly lower number of layers than what is predicted. Due to the absence of structuration rate, it is possible to perform worse than the prediction model. Thus, an exact material structuration rate, A_{thix} , is crucial to properly perform the validation test for future study.

Also, geometric imperfections were found at layers 10 and 20 during the printing process which was caused by reduced nozzle speed for unknown reasons. A slight lagging of 3D printer caused an excessive deposit at a point which causes the defects. This factor also contributes towards the poor performance of the material in the 3D printing process.

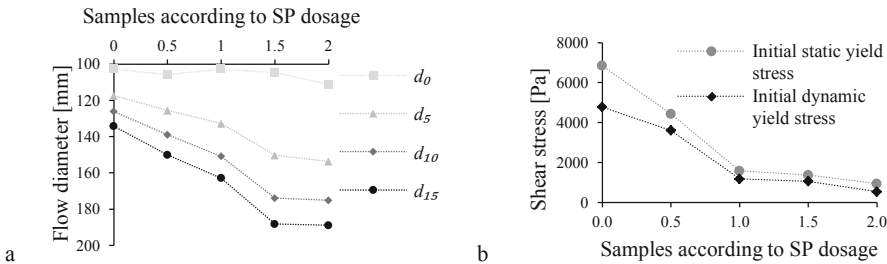


Fig. 7. a. Spread flow diameter at 0, 5, 10 and 15 vertical drops, i.e. d_0 , ..., d_{15} . The horizontal axis represents the test sets, S_0SP to S_2SP (left to right); b. Initial static and dynamic yield stress against test sets with different superplasticizer dosage.

5 Conclusion and Future Works

In this study, an attempt was made to correlate rheological parameters obtained by a sophisticated measuring device and a slump flow table test with impact loading, which has much simpler yet compendious execution. Based on the measured results, a strong and direct correlation between the two measurements is not made, due to a limited number of samples and a remarkable superplasticizer dosage difference.

However, this study can be extended to a quantitative assessment to further investigate an empirical correlation. Ongoing work aims to develop an adjusted analytical model of the mini-slump with the inclusion of impact loading and varying contact area.

From the results above, a suggestion of this indicative parameter, flow table diameter, for 3DCP is proposed in Table 7.

Table 7. 3DCP printability according to the flow table diameter reading ranges of the test results.

Readings [mm]	−130*	130–150	150–165	165–180	180+
Suggestion	×	△	○	△	×

*This may be printed with a presence of external energy source, e.g. poker vibrator. But, poor quality of 3DCP is expected.

- ×: Not recommended for 3DCP as the material exhibits a drastic fresh behavior of being either overly stiff or flowable.
- △: It may be acceptable for 3DCP. However, it may possibly result in a poorly printed object or poor buildability performance.
- ○: It can be acceptable for 3DCP.

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Effect of Metakaolin, Fly Ash and Polypropylene Fibres on Fresh and Rheological Properties of 3D Printing Based Cement Materials

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Abstract. The aim of this paper is to investigate the effect of mix composition such as the percentages of metakaolin (MTK) and fly ash (FA) on the fresh and rheological properties and also the percentage of polypropylene fibres. Several tests were used to determine the rheological properties such as the flow table test, the cylindrical slump test and penetrometer test. The estimated yield stress values were then calculated from the results of cylindrical slump test and the fresh density of mortar.

The extrusion of layers for 3D printing was carried out using a controlled air pressure gun. This tool made it possible to test the extrusion of each mortar mix directly after mixing by producing several layers on top of each other. The use of MTK had a significant effect on the fresh and rheological proprieties. It was observed that replacing cement with MTK led more cohesive and dry mixes and therefore difficult to extrude. Using a combination of FA and MTK has increased the yield stress, cohesion, reduced the penetration and improved the shape stability and printability. It also reduced bleeding and segregation. Finally, adding more polypropylene fibres reduced the workability by improving the cohesion with a denser fibre network and reduced the penetration. Thus led to an increase in the yield stress and a reduction of the fresh properties. Good relations were observed between the fresh and rheological properties.

Keywords: 3D printing · Metakaolin · Polypropylene fibres · Penetration · Slump flow · Yield stress

1 Introduction

3D printing in civil engineering includes four different processes that have been invented so far: Contour Crafting (US), Concrete Printing (UK), D-shape (Italy) and Smart Dynamic Casting (Switzerland). Among digital concrete methods, extrusion-based 3D printing is probably the most developed technique. Recent researches on 3D printing have conducted some investigations on the mix-design, rheological and process related issues [1–6].

Concerning binder's composition, it has been concluded that adding 24% of fly ash, 8% of silica fume and using natural fibres from 0.2 to 0.6% results in great printability properties, improvement in rheological and fresh performances and in bleeding and segregation resistance. Plus, the addition of nanoclay-based viscosity modifying agent (VMA), Actigel, has proved to be efficient in developing 3D printing essential characteristics [5, 6].

The objective of this study is to evaluate the effect of different mix compositions such as 10 to 15% of metakaolin, 30% of fly ash and percentage of polypropylene fibres (1.2 to 3.6 kg/m³) on the fresh and rheological properties of a printable mortar using layers extruded with a simple modified joint gun, and the rheological and fresh properties of different mix designs were evaluated.

2 Printing Process

The essential properties for a mortar to be printable are: extrudability and the resistance to deformation of the layers under their own weight and that of the following layers at fresh state. Both parameters depend on the rheological properties of the fresh cement paste [7, 8].

Extrudability is associated with the ability of the material to pass through the nozzle of the printing equipment, depending on its consistency and workability of the mixture. For a mortar to have good workability, bleeding and segregation must be avoided, and the mortar must be not too fluid in order for each printed layer to sustain its own weight and the weight of the upper layers. Extrudability is mainly influenced by the water/binder ratio, sand/binder ratio and chemical additives of the mix design such as superplasticiser [4–6].

In addition to low deformability at fresh state, layers must also bind to each other to form a uniform and rigid whole. This layer bond depends mainly on the printing process (time between deposit), nature of surface layer and mix proportions. The printability of a mortar can be assessed through the opening time. This parameter, also called time interval, represents the maximum time interval over which printability can be achieved in a suitable way. Opening time should be neither too long nor too short. If the time interval is too long the bonding between the layers will be weak, while if it's too short the mortar will be unextrudable [1].

3 Experimental Programme and Methods

In this investigation, the 3D printing was carried out by extruding layers of mortar with a compressed air gun. The compressed air gun had a capacity of 5.2×10^{-4} m³. A single pressure of 2 bar was used for all mixes. The shape of the nozzle was carefully chosen to achieve cross section of 24×14 mm². The nozzle had a ribbed inner surface to ensure good cohesion between the superimposed layers. The effects of addition of PP

from 1.2 to 3.6 kg/m³ in reference mix, replacement of cement by 30% FA, and replacement of cement by 10 to 15% MTK were investigated on fresh properties and extrudability of 3D printing mortars.

3.1 Mix Design

Table 1 presents the mixtures investigated in this research. The binder used was an ordinary portland cement CEM1 52.5 N according to BS EN 197-1:2011. Fly ash (FA) with particle density of 2210 kg/m³ complied with BS EN 450-1:2005 + A1:2007. Metakaolin (MTK) is a highly processed form of kaolin clay, which is a mineralogically complex hydrous aluminium silicate, white in colour with a dull lustre. It is a processed material, calcined in kilns to form highly reactive material known as MTK. MTK is a pozzolan, which is a material that, when mixed with water will chemically react with calcium hydroxide at normal temperatures to form compounds possessing cementitious properties (density = 2.2 kg/m³).

The sand used had particle size between 0 and 4 mm, absorption coefficient of 0.30 and density of 2650 kg/m³. Before mixing the sand was dried and sieved with a 1.18 mm sieve using a shaking table. The sieve size was chosen to obtain a thinner paste and therefore achieve a better extrudability of the mortar and an easier printing process. Moreover, this particle size allowed using a viscometer.

The sand/binder and water/binder ratios were kept constant for all mixes at 2 and 0.5 respectively. Similarly, the water temperature was maintained at around 16 °C for all mixtures.

SP from modified polycarboxylic ether fluid was used as an aqueous solution with a solid content of 30% and specific gravity of 1.05. Polypropylene (PP) fibres were also used which are monofilament FIRBIN fibres with 6 mm long and diameter of 100 µm. The fibres used at dosage of 1.2 and 2.4 kg/m³.

The mixing procedure required the use of a 2.5 L capacity mixer. To avoid materials to go over the mixing bowl while the mixer is on, different volumes of cement paste have been calculated up to 2.2 L. This blender allows two different speeds, which will be referred to later on by low (140 rpm) or high speed (285 rpm). First of all, dry materials are positioned in the mixer: binders as cement and fly ash, and sand. In order to obtain a good particles repartition, the blender is turned on for 30 s, on the first speed (low).

Secondly, water mixed with superplasticiser is inserted into the mixing bowl: this is when the time counting starts ($t = 0$). Binders, sand, water and SP are then mixed for 30 s at low speed. Finally, PP fibres are added to the mix and blended for 30 s at low speed.

To ensure good repartition of fibres and a proper cohesion of materials, the mix is blended for 2 min at high speed. Finally, the mixture is blended a last time at low speed for 1 min for the mixture to settle. At this stage, the mortar is tested for rheological and fresh characterisation, as described in the test methods section.

Table 1. Mix design of mortar tested (kg/m^3).

Mix Code	C	FA	MTK	W	Sand	SP	PP
REF-PP1.2	607	0	0	305	1230	0.136	1.2
REF-PP2.4	607	0	0	305	1230	0.136	2.4
REF-PP3.6	607	0	0	305	1230	0.136	3.6
FA30-SP0.2-PP1.2	435	172	0	305	1205	1.213	1.2
FA30-SP0.2-PP2.4	435	172	0	305	1205	1.213	2.4
REF-MTK15-SP0.44-PP1.2	516	0	91	305	1225	2.671	1.2
FA30-MTK15-SP0.44-PP1.2	334	182	91	305	1180	2.671	1.2
FA30-MTK10-SP0.44-PP1.2	364	182	61	305	1184	2.671	1.2

3.2 Testing Procedure

Two simple tests have been performed on every single mortar mixture to define the fresh properties of mortar: the penetrometer test and the flow table test. In order to describe pastes rheological properties, a semi-empirical test, slump test, have been employed. Indeed, right after mixing, the first test is the penetrometer test, followed by the flow table test and then by the slump test. The duration of every test (penetrometer, flow table, cylindrical slump test, density) was carried out in less than $3 \text{ min} \pm 1 \text{ min}$. After that, the density of the mix is measured. It is important to note that the mortar is mixed by hand during 15 s before each test and the density measurement.

The standard BS ISO 13765-1:2004 characterises the use of the cone penetrometer. In fact, this test aims to determine the workability and the consistency of the mortar under a certain stress caused by the dropping cone (only under gravity). Firstly, the cement paste is introduced in the conical mould in two layers. In order to have a homogeneous filling and to avoid voids in the moulds, each layer is compacted with ten short strokes. The excess of mortar is removed using a trowel or a spatula and the mould is placed under the dropping cone. Then, the testing machine is adjusted so the cone just touches the surface of the sample. Finally, the button is pressed for 5 s and the cone is released: it penetrates into the mortar sample under its own weight. The value read on the dial is noted: this penetrometer allows a precision of 0.01 mm. The cone is then dropped 3 more times in order to have more values and so the mean value will be more precise.

The flow table test was used to measure the stiff mix consistency by taking the spread of the mortar under a certain type of stress (jolting; BS EN 1015-3:1999). The first step is to place the conical mould centrally on the flow table. The mortar is then introduced in two layers; each layer is compacted by ten strokes. The mould must be maintained properly when filling it. The excess of mortar is then removed. After 15 s, the mould is slowly and vertically lifted: two values of both diameter of the slump (two perpendicular directions) and height are measured. Finally, the sample is spread out on the flow table by jolting: 15 jolting in 15 s are required. Afterwards, measurements are taken another time: two perpendicular diameters of the spread.

The third test is quiet similar in execution then the previous one: the slump test. Indeed, the procedure followed for this test is similar to the flow table test, previously exposed: the cylindrical mould is centrally placed onto the flow table; the mortar is introduced in two 10-strokes-compacted layers into the mould (firmly maintained); the excess of mortar is removed to have a plain surface and the mould is lifted after 15 s; finally, two values of both heights and diameters are written down in order to have more precise averages. However, this semi-empirical test allows estimating the static yield stress of the mix depending on the ratio height/spread. Three different flow regimes exist with an important stress tensor difference: when $H \gg R$, $H \approx R$ and $H \ll R$ – where H is the height and R is the radius after the mould's lift [7] – See Fig. 1.

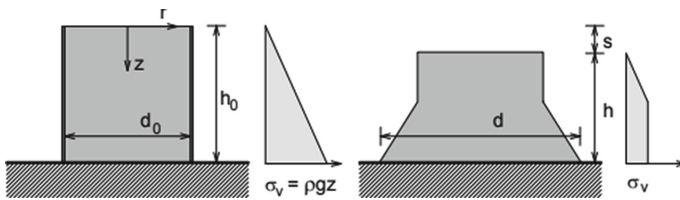


Fig. 1. Notations for estimating the yield stress with the slump test [7]

After these previous tests, the density is taken in a cylindrical mould filled with two layers of mortar, each of them compacted by 10 strokes.

For the opening time procedure, every time 15 min of measurement, the mortar was remixed and the tests were conducted such as the penetration test, the flow table and the slump test through time during 135 min.

4 Results and Discussion

4.1 Fresh and Rheological Properties

In this section the results of the penetration test, flow table, slump test and portable vane carried out on the different mixtures are reported and discussed. All results are summarized in Table 2.

Table 2. Fresh and rheological results [kg/m^3]

Mix	Penetrometer (mm)	Flow table Spread (mm)	Slump test (mm)	Vane test yield stress (Pa)
REF-PP1.2	33.3	224.0	110.0	1286
REF-PP2.4	21.3	213.5	113.5	1360
REF-PP3.6	20.0	173.5	124.0	1507
FA30-SP0.2-PP1.2	38.6	233.0	106.5	1334
FA30-SP0.2-PP2.4	29.6	205.5	117.0	1674
REF-MTK15-SP0.44-PP1.2	28.2	190.0	121.5	1464
FA30-MTK10-SP0.44-PP1.2	28.7	200.0	122.0	1444
FA30-MTK15-SP0.44-PP1.2	36.4	206.0	117.0	1369

4.2 Effect of Binders and Fibres

It was observed that fly ash improved the extrusion of mortar, and can be extruded for long time compared to reference mix (100%C) due to none-early reaction of FA (see Sect. 4.4). Mix with FA helped also to have a better cohesion between layers. However, as shown in Table 2, adding Fly Ash has opposite effect on the two reference mixes which differ only by the amount of PP fibres. The fact that bleeding is reduced when FA is added may be explained by the size and shape of the particles. The surface area of FA particles is $420 \text{ m}^2/\text{kg}$ while that of cement is $370 \text{ m}^2/\text{kg}$, therefore more water is needed to cover the surface of the particles. In addition, cohesion and segregation improved and reduced respectively by replacing part of the cement with FA, due to the ball bearing effect of the particles. FA is known as an extrusion improving additive because the spherical shape of its particles acts to decrease rheological parameters (yield stress and plastic viscosity). However, the increased FA content may result in reduced workability due to absorption of the SP [8].

As FA, also MTK allows for better extrusion, longer extrusion time and better buildability and cohesion of the layers. MTK particles have a flat shape with a very large specific surface area per unit volume. In addition, the silicate and aluminate contained in the MTK make pozzolanic particle surfaces reactive. These properties of MTK particles have led to an extremely high water demand. As a result, the pore volume of the binder has been greatly reduced due to the efficient consumption of water in hydration reactions [9].

As the specific surface of MTK is equal to $1410 \text{ m}^2/\text{kg}$ while that of cement is $370 \text{ m}^2/\text{kg}$, bleeding reduced considerably and cohesion improved, which explains the greater fresh and rheological properties obtained with a higher MTK dosage.

We can therefore conclude that metakaolin is a suitable material for 3D printing since it improves the rheological properties of mixes. Moreover, adding 15% metakaolin is more beneficial than a 10% dosage.

When FA is added to MTK, the rheological properties are homogeneous. As the slump flow decreases this confirms the usefulness of MTK in cementitious mixtures for 3D printing. The increase in fibre content affected the handling and cohesion of the

material. The fibres created a connected mesh that improved the fresh and rheological properties as better cohesivity of the mix which led a better buildability and stability of the shape of layers. However, high percentage of fibres can lead a blockage of mortar in the gun [4–6].

4.3 Correlation of Rheological Properties

The flow table and penetrometer tests are good indicators for determining the consistency of mixtures and therefore the workability of the mortar. These measurements correspond to the fluidity of the material or, conversely, its cohesion, and make it possible to evaluate its deformability of the material when it is subjected to a certain type of stress. In Fig. 2, the slump flow values are plotted as a function of penetration. As expected, this figure shows that when slump flow increased, the penetration also increased.

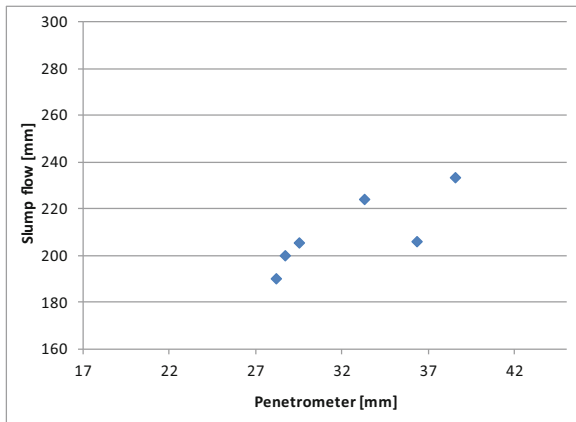


Fig. 2. Variation between slump flow and penetration

The main parameter that can be determined from this experimental program is the yield stress of the mixtures. Due to the need for a rigid mixture to be extrudable, the yield stress of the mixtures studied cannot be evaluated using the traditional rheometer. Therefore, a semi-empirical formula is used which links the static yield stress to the deviations and heights of the cylindrical collapse test.

As mentioned previously, three regimes are used to estimate this rheological parameter: $H \ll R$, $H \approx R$ and $H \gg R$. In this case, $H \ll R$, i.e. fluid mortars, was not appropriate. Depending on whether the cement paste has an intermediate or rigid consistency, the cases $H \approx R$ and $H \gg R$ are used according to the visual ratio and the R/H ratio [7].

The previous analysis of fresh and rheological properties shows a certain link between the flow table and the estimated yield stress. Generally, when the slump flow reduced, the estimated yield stress increased. This trend can be observed in Fig. 3 which presents all the results of this investigation.

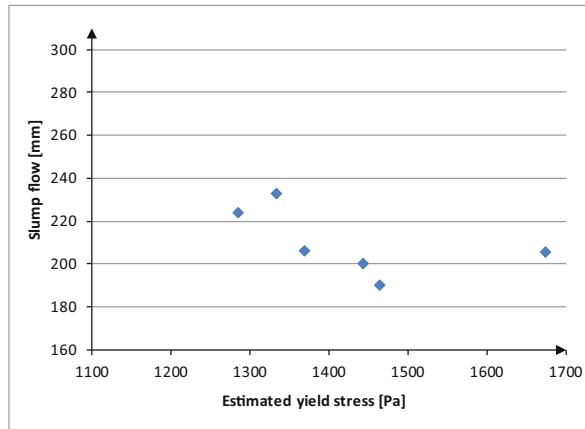


Fig. 3. Variation between slump flow and yield stress

Figure 4 presents all penetration results as a function of the estimated yield stress values. The graph shows that penetration and yield stress estimation are inversely proportional: the greater the estimated yield stress increased, the lower was the penetration value.

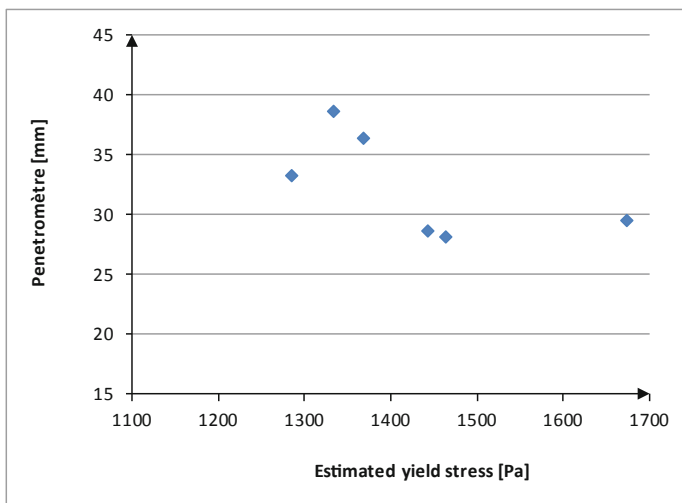


Fig. 4. Variation between penetrometer and yield stress

4.4 Opening Time

Figure 5 shows the flow test results and estimated yield stress measured at different testing times up to 140 min. As it can be observed the curves of the two reference mixes have better estimate of yield stress and lower penetration and flow compared to the fly

ash mixtures. This suggests that fly ash takes longer to react. Indeed, the pozzolanic behaviour of FA and the size of its fine particles improve the fresh and rheological properties of mixtures but only after a certain time. As a result, FA can help to maintain the consistency and workability of the mortars over a longer period of time. The limit of observed mixture printability has been also plotted describing printable boxes for each formulation.

As also shown in Fig. 5, the estimated yield stress increased with a higher amount of PP fibres in the mixture, while penetration and flow decreased. This can be due to a larger mesh size created by the fibres which make it is more difficult for the cone of penetrometer to penetrate in the mortar. Similarly, this mesh size allows the flow to be retained during the flow table test. Rheological properties are therefore improved with an optimum of fibres. However, high addition of fibres can create an increase in connectivity of network between fibres and can prone to stiff mix leading to possible of reducing the extrusion time.

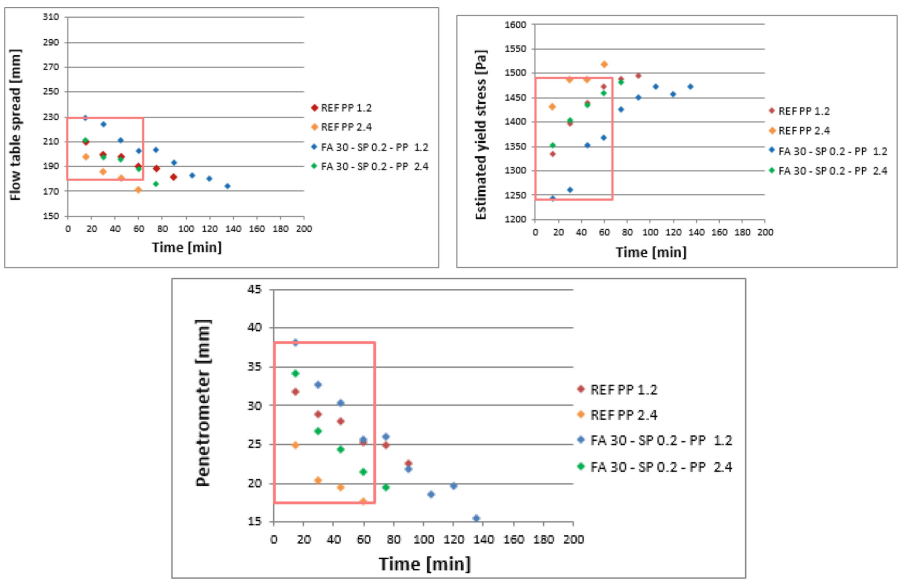


Fig. 5. Printable box of 3D printing mortar

5 Conclusions

This experimental study aimed to analyse the effects of different mix components on the rheological and fresh properties of 3D printable mortars. The different mixes were assessed based on the results of penetration test, flow table, the portable vane. Rheology was evaluated by determining the estimated yield stress. Mortar layers were produced by extrusion using a compressed air gun.

Based on the above tests the following conclusions can be drawn:

- FA and MTK increased the fresh and rheological properties of the mortars and the optimal mix proved to be a combination of both components in terms of workability and extrudability.
- The use of MTK in combination with cement appears to have a significant impact on the behaviour of 3D mortar. The mix showed to be more rigid and dry and therefore difficult to extrude.
- Using a combination of FA and MTK increased the yield stress, cohesion, stability and printability. It also reduced the bleeding and segregation and improve the stability.
- The fibres reduced the slump flow by improving cohesion through a denser fibre network. The highest percentage of fibres led to an increase of the yield stress and decrease of workability.
- Printability box with opening time was established for the mixes investigated in this paper.

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“The Slug Test”: Inline Assessment of Yield Stress for Extrusion-Based Additive Manufacturing

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Abstract. Successful and efficient fabrication using robotic extrusion of cementitious materials mainly relies on the mastering of the printable material fresh state behavior. This paper tackles this aspect by introducing a novel rheological apparatus dedicated to the yield stress measurement at nozzle exit in extrusion-based manufacturing. It is based on the analysis of the specific gravity-induced flow that takes place at nozzle exit, which is at the origin of the formation of material drops or so-called “slugs”. Using a simple connected balance with a high measurement frequency gives access to these slugs average mass and, in turn, to the yield stress. Due to its convenience, the protocol is appropriate for setting the printing parameters according to the yield stress measurement at the nozzle exit in order to ensure successful fabrication.

Keywords: Robotic extrusion · Additive manufacturing · 3D printing · Rheological properties · Measurement apparatus

1 Introduction and Context

In large scale Concrete 3D Printing or more specifically Robotic Extrusion of cementitious material, a given object is built from continuous pumping, extrusion and deposition of an essentially one-dimensional lace of mortar, following a printing path defined from the object geometry [1]. As new layers are continuously added on previous ones, effective loading on the first layers is gradually increasing. To prevent the collapse of the object, the structuration rate, i.e. the evolution of yield stress through time, is a critical parameter. It was shown that this increase should be linear or cubic with time to respectively prevent plastic failure and buckling collapse [2–4]. Depending on the object slenderness (height/width object ratio) and curvature, the time between two layers would be either limited by robot speed for smallest values, or by the structuration rate for slender structures. In this last case, the structuration rate is then the limiting point. Within this frame, few tens of Pascal per second seems to be a reasonable order of magnitude, assuming that the yield stress value should go from hundreds of Pascal, for efficient pumping, to hundreds of Kilopascals, to withstand a 2 m height structure in a few hours.

Rheological requirement of extrusion-based additive manufacturing also includes the yield stress value at nozzle exit [4]. In literature, different ways of shaping laces can be found [5], either using nozzle geometry, called extrusion lace shaping, or by pressing it onto the precedent lace, called oriented lace pressing. In the first case, the yield stress should be sufficiently high for the layer to support its own weight without deformation [4]. In the second case, the yield stress should be sufficiently small to limit the pressure needed for lace forming during deposition [6] that acts on the entire object being printed. It is worth noting that the yield stress requirement at nozzle exit would also vary depending on the object geometry and printing strategy, such as the presence of cantilevers [7, 8] or curvatures [9].

The printing technology used in the present paper belongs to the Build’ in platform at Ecole des Ponts Paristech and was designed by XtreeE and is shown in Fig. 1. It precisely aims at combining small geometrical tolerances with high flexibility on the object shape within fast printing. This capacity calls for the use of a very thixotropic cementitious material that requires the continuous addition and dispersion of accelerator into the initial mix just before the nozzle exit [10].

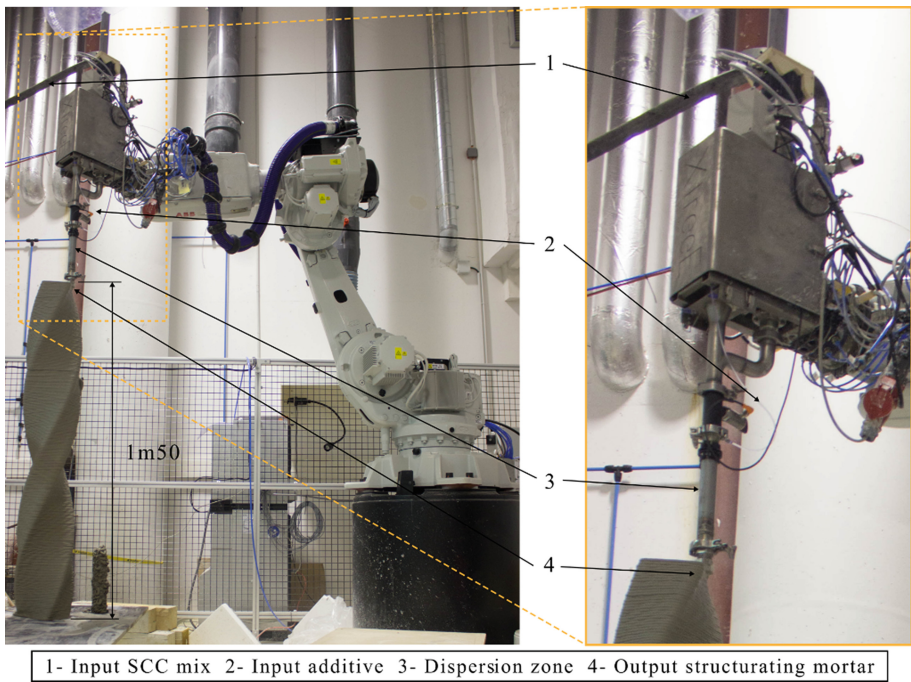


Fig. 1. Printing device used in this work, designed by XtreeE ® for build’ in platform. More information on the principles is provided in [7].

The accelerator was found to turn the initial self-compacting fine-grained concrete (SCC) to a very reactive material with a structuration rate that depends on dosage in a suitable range for high productivity robotic extrusion of concrete (≈ 10 Pa/s). As an

example, the 1.8-meter-high tower, shown in Fig. 1 was printed within 20 min. However, the yield stress measurement of such a high structuration rate material is a challenging perspective. On one hand, due to its thixotropic behavior, the cementitious materials shows a yield stress value at nozzle exit highly dependent on the very complicated shear rate history brought by the process. This property prevents therefore from assessing independently non-extruded samples in usual rheometers. On the other hand, such a high structuration rate prevents from using standard tests, such as Abrams cone [11] or simple compression [12, 13] just after extrusion, as the material evolves too fast to be transported and tested.

The present contribution proposes a simple and reliable test to perform instantaneous yield stress measurement of very thixotropic extruded materials at the nozzle exit. The test is performed by studying the gravity induced flow at nozzle exit. This flow is specific to yield stress materials and is characterized by the formation of cylindrical drips, called here “slugs”. This effect has been studied for various food industry applications by [14]. The formation of a drip is illustrated for “mayonnaise” in Fig. 2-a and evidenced for printable concrete in this paper (Fig. 2-b).

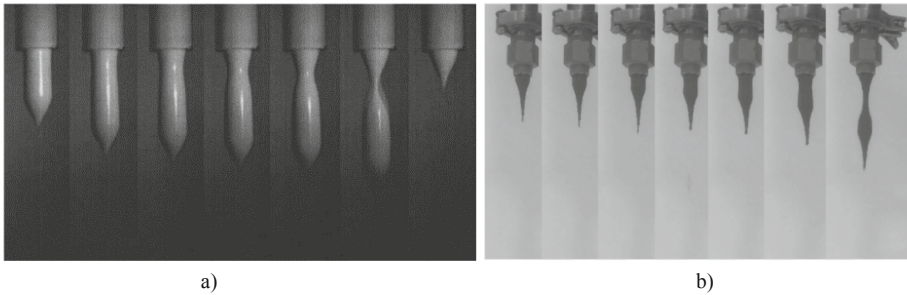


Fig. 2. Successive views of slug formation: a) Mayonnaise at syringe exit, reproduced from [14]
b) 3D printed concrete at nozzle exit

We suggest here that, in the case of most printable materials of interest, such a discontinuous flow finds its main origin in the local yield stress of the material and is not affected by surface tension σ when the yield stress τ_c is sufficiently high $\sigma/R_0 \ll \tau_c$ (σ : the surface tension and R_0 : the radius of the nozzle).

In this paper, the measured concrete slug mass is showed to be a good indicator of the yield stress values of the tested materials. In the first subsection, materials and protocols of the slug test are described. Then, experimental results for non-thixotropic materials are presented and compared with traditional slump test using Abrams cone [11]. Finally, in the last section, the analytical analysis of the slug formation process proposed in [14] is adapted.

2 Materials and Protocols

2.1 Materials

Experiments were run using a high performance printable mortar made from NAG3 premix provided by Larfarge-Holcim, a small amount of short glass-fiber, water and phosphonate based superplasticizers “Fluid Optima 100” from Chryso. Mixing proportions are provided in Table 1. In this specific study, the accelerator is replaced by an aqueous solution of Polyacrylamide (PAM) 6 g/L. Its addition to the mix induces a strong structuration through polymer bridging of the cement particles [15]. Moreover, it was also found that it dramatically retards the hydration of cement by releasing superplasticizer particle in solution, which, in turn, provides a stable yield stress during a long period of time (many hours). Although, this last property is not very suitable for robotic extrusion, it offers the possibility to compare the present measurement procedure, to the slump test using Abrams cone described in [11], on the same material. Thanks to the advanced printing technology used in this paper, PAM is continuously added to the mix and dispersed in the print head on a distance of 10 cm using dynamic mixing before final extrusion and slug formation from a 20-mm-diameter nozzle. This dispersion distance was found to be a trade-off between dispersion quality and preservation of the PAM integrity. Moreover, it allows for obtaining different consistencies from a single initial batch, as the increase of yield stress directly depends on PAM dosage, which can be modified throughout the experiment.

Table 1. Mixes proportions

Components	Fibred SCC mix
NAG3 Premix (kg)	50
6 mm Glass fibre (kg)	0.200
Water (kg)	4.8
Fluid Optima 100 (kg)	0.215

2.2 Experimental Set-Up

The acquisition (Fig. 3) set-up only relies on a simple balance Kern model IFS 30K0.2DL. The original interface was replaced by an external power supply linked to the load sensor and acquisition was made using a National Instrument acquisition device (USB-6008) with a measurement frequency of 10 kHz and a 12 bits range for analogic input. The sensor range goes from 0 to 50 kg between 0 to 10 V. The standard deviation is measured using 80000 points and is equal to 41.7 g. The precision is then enhanced using sliding mean filter on 800 acquisitions and by sampling at 25 Hz. The final sampled signal has a standard deviation of around 1.5 g. A typical raw and sampled signal obtained during a slug test is plotted at the right-top corner of Fig. 3. On this graph, slug impacts are clearly visible before the balance quickly reaches a stable value. The difference between two stable plateau values is simply the slug mass. As a consequence, thanks to the piecewise shape of the mass versus time plot, it can provide

both concrete flow rate and typical slug mass. As the characteristic time of the impact was found to be about 0.1 s, the discrete derivation is then performed on the sampled measurement. The obtained derivate signal is illustrated in yellow at the bottom graph of Fig. 3. A slug detection occurs when a rising edge on derivate mass signal reaches a given threshold value, taken equal to 2 times the standard deviation on the derivate signal, which proved to be a robust way to detect slug impact over noise. Each slug mass is computed using a half of the number of data separating previous impacts. Respective piece wise function is illustrated in purple in Fig. 3. Resulting slug mass measurement error is then around 0.5 g. Concerning flow values, they are calculated from the least square affine fit on the sampled data.

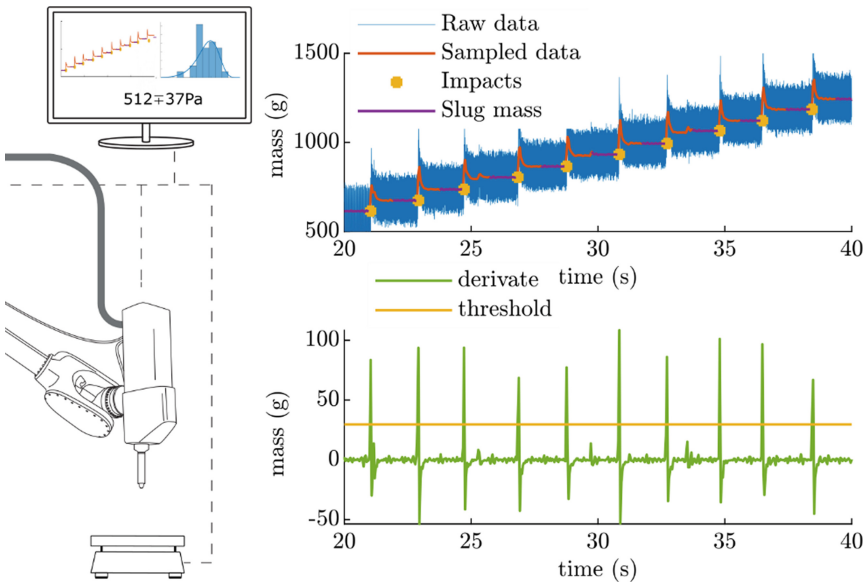


Fig. 3. Schematic acquisition set-up and typical acquisition.

3 Experimental Results

3.1 Slug Test

Six different situations are explored during this experiment combining three different levels of flow and two levels of PAM addition into the mix. First of all, one can observe the clear separation between the two levels of PAM dosage. As expected, more PAM in the mix results in an increase in slug mass. However, the effect of flow level is not clear and seems to be quite negligible for the typical flow rate values used in additive manufacturing. At the smallest flow rates (far lower than the typical printing ranges), an interesting situation occurs where the mean value of slug mass either dramatically decreases for smaller PAM dosages or increase for higher PAM dosages.

The slug masses distributions of two typical cases ($PAM/SCC = 6 \text{ g/kg}$, $Q = 12 \text{ g/s}$) and ($PAM/SCC = 7.5 \text{ g/kg}$, $Q = 33 \text{ g/s}$), also used for direct comparison with slump test, are detailed in Fig. 4. Slug masses is computed from the mean value of the distribution of mass and error from the mass standard deviation σ_m and the number of slug n using $2\sigma_m/\sqrt{n}$, respective apparent yield stress values are computed and using Eq. (2) with $g = 9.81 \text{ m/s}$ and $R_0 = 10 \text{ mm}$. One can observe that standard deviation of slug masses are more important for the lowest value of PAM/SCC ratio. This suggest that the yield stress assessment with sufficient precision would require more slug. Nevertheless, for the same amount of extruded concrete, smaller slug mass goes with a higher number of slug n . Consequently, the precision on the yield stress estimation increases with the used concrete quantity. In this study, the acquisition duration was modified depending on the concrete flow and between 1 and 2 kg of material for each acquisition were used.

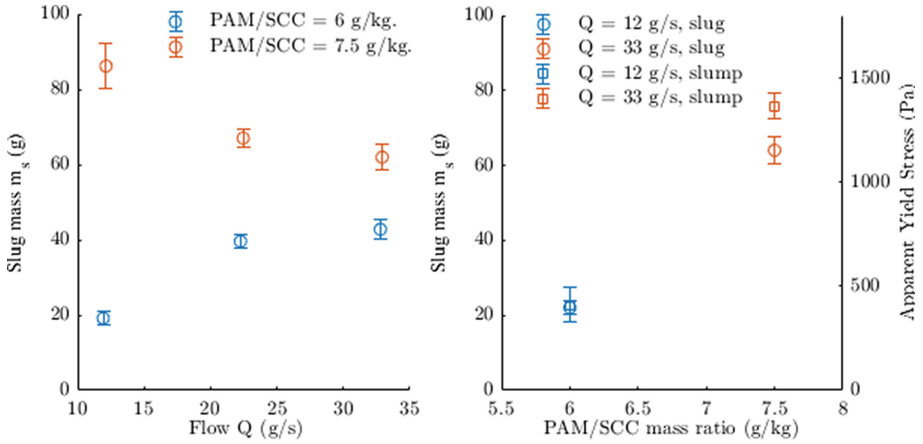


Fig. 4. Slug mass depending on concrete flow and PAM/mortar ratio and comparison between yield stress value determined using both test. The number corresponds to the experimental order.

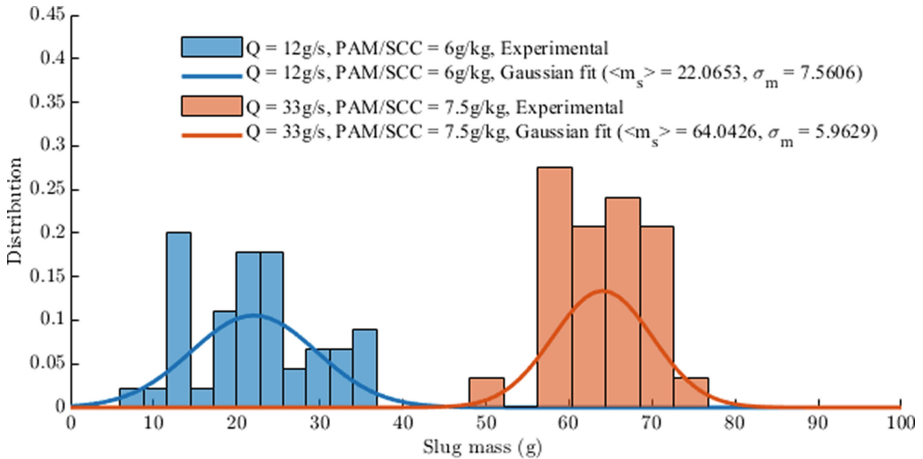


Fig. 5. Experimental distribution and theoretical Gaussian of slug masses.

As illustrated in Fig. 5, resulting measurement errors from the mass standard deviation σ_m and the number of slug n computing using classical formula of Gaussian error $2\sigma_m/\sqrt{n}$ was equivalent or lower than slump test using significantly less material.

3.2 Slump Test

Due to the relative large volume needed to performed the slump test (6L) compared to the volume of the batch ($\pm 20L$). Slump tests are realized only on two mentioned cases standard Abrams Cone. The printing head was placed above the cone to fill it without changing the processes parameters to ensure that the tested material was still the same. Slump value was measured and yield stress was computed using the dimensionless plot related to the ASTM Abrams cone given in [11] (Fig. 5). The yield stress value are gathered and compared with respective data from the slug test in Table 2. Graphical comparison is also given on the right plot of Fig. 4. The obtained slump test yield stress values are similar to the ones computed from slug tests, although slightly higher, which to our mind come from structuration in the initial batch.

Table 2. Experimental results of slump test using ASTM Abrams cone and comparison with Slug test values.

Case	h (mm)	Yield stress (Pa) (slump test)	Yield stress (Pa) (slug test)
PAM/SCC = 6 g/kg, Q = 12 g/s	226 $\pm$ 5	411 $\pm$ 83	398 $\pm$ 32
PAM/SCC = 7.5 g/kg, Q = 33 g/s	148 $\pm$ 5	1368 $\pm$ 63	1155 $\pm$ 64

4 From Slug Mass to Rheological Properties

The starting point for the yield stress identification is the relation between dimensionless slug length λ , dimensionless extrusion flow v derived in [14] for a Herschel-Bulkley fluid.

$$\lambda(\lambda - 1)^{\frac{1}{n}} = v \quad (1)$$

With $\lambda = \frac{\rho g X}{\sqrt[3]{3\tau_c}}$ and $v = \left(\frac{K}{\tau_c}\right)^{\frac{1}{n}} \frac{\rho g V}{\tau_c}$ where X is the slug length, V , the extrusion speed, ρ , the density, g , the gravity acceleration, and τ_c , K , n are respectively the yield stress, the consistency index, and the flow index.

Solution for a Perfectly Plastic Fluid

In this paper, we decided to consider our extruded mortars as a perfectly plastic material, i.e. $v \ll 1$ and $\lambda = 1$, neglecting therefore any potential viscous contributions.

Replacing the slug length X by the slug mass $m_s = \rho X \pi R_0^2$ with R_0 the radius of the nozzle, we obtain a simple expression relating yield stress to the measured slug mass:

$$\tau_c = \frac{g m_s}{\sqrt{3}\pi R_0^2} = \frac{g m_s}{\sqrt{3}S} \quad (2)$$

One can recognize the expression of the direct traction stress at nozzle exit under self-weight, $\sqrt{3}$ comes from the Von Mises plasticity criterion and the section πR_0^2 can be replaced by the nozzle section S . By weighing a sufficiently high number of drops, an accurate estimation of the yield strength can be obtained.

5 Conclusion

The proposed apparatus is able to measure the yield stress value at nozzle exit for a large range of values from hundreds to thousands of Pascals. The test can be performed simply by collecting a given number of concrete slugs at the nozzle exit and weighting them. The comparison with the traditional slump test using ASTM Abrams cone shows that it is an accurate apparatus to measure yield stress at nozzle exit with significantly less material amount needed.

Although the advancing printing technology using continuous addition of PAM is interesting for direct comparison with the Slump test, it also brings difficulties due to the strong structuration that occurred when PAM is added to the concrete. Indeed, it was noticed that a too fast structuration prevents a stable extrusion flow.

Thanks to acquisition set-up using a connected balance, a simple signal processing permits to capture automatically the yield stress value at nozzle exit, just before starting the printing. It allows for modification of the printing parameters to ensure optimal robotic extrusion, or, when advanced printing technology is used, the additive/concrete ratio can be dynamically optimized to obtain the needed yield stress at nozzle exit.

The presented acquisition set-up also permits to get the distribution of slug mass of each acquisition. This element permits not only to precisely estimate the measurement error, but also to give information on the homogeneity of the mix. Indeed, larger standard deviation is probably linked to greater heterogeneity.

Homogeneity assessment is of great interest when additive or additional components, such as short fiber [16], are added and mixed in the printing head just before nozzle exit. The slug test could be an interesting tool to improve advanced printing technology. This aspect will be discussed more into details in future publications and during the conference.

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Fresh and Hardened Properties of 3D-Printed Concrete Made with Dune Sand

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Abstract. This paper examines the performance of 3D-printed concrete made with locally abundant desert dune sand. Cement was replaced by up to 10% silica fume and 30% fly ash to reduce its detrimental environmental footprint. The water-to-binder ratio used in the mix ranged between 0.35 and 0.40. Also, a superplasticizer was added in the range of 1 to 3%, by binder mass. Concrete mixes were proportioned to attain optimum fresh and hardened properties. A control mix with crushed dolomitic limestone aggregates served as a reference. The performance of 3D-printed concrete mixes was assessed based on slump flow, pumpability, and compressive strength. Experimental results showed a reduction in slump flow and pumpability with an increase in dune sand content. In turn, the compressive strength increased by 3% when 20% dune sand was utilized, but decreased by an average of 3% for every additional 10% subsequently. Concrete mixes incorporating a superplasticizer and higher water-to-binder ratio exhibited improved workability. While the former caused limited change to compressive strength, the latter resulted in a notable decrease. Upon replacing cement with silica fume and fly ash, the slump flow and pumpability increased. In fact, 3D-printed concrete made with 3% superplasticizer, 20% fly ash, and 10% silica fume experienced a 230 and 79% increase in slump flow and pumpability, respectively. Compressive strength increased by an average of 4% for every 10% fly ash replacement. The incorporation of 10% silica fume improved the strength by an additional 14%. Analytical models were developed to correlate slump flow to pumpability and 3D-printed concrete compressive strength to that of typical concrete cubes, serving as guidelines to produce optimal concrete mixes for large-scale concrete 3D printers.

Keywords: 3D printing · Dune sand · Concrete · Fresh properties · Hardened properties

1 Introduction

The construction and building industry have shown great interest in 3D printing technology over the last few years [1–3]. The process of 3D printing of concrete entails the extrusion of a cementitious mixture to form a layered product. It has been labeled as “digital manufacturing” and “automated construction”, owing to its link to data of a 3D model and dependency on some degree of automation [4]. This technology promises to eliminate the need for formwork and labor while casting concrete. As such, its

rheological properties, including pumpability and slump, are critical to its proper implementation in construction applications [4].

Past literature has investigated the rheology of fresh 3D-printed concrete. Roussel [4] studied and correlated the rheological properties in terms of yield stress, elastic modulus, viscosity, critical strain, and structuration rate. In turn, Tay et al. [5] investigated the slump, slump flow, pumpability, and buildability of 3D-printed concrete. A pumpability index value was also introduced and associated with buildability. Authors reported that mixes with slump and slump flow values in the range of 4–8 mm and 150–190 mm, respectively, resulted in a smooth surface and adequate buildability. Further tests, including print quality and shape stability, were proposed to assess the rheology of different 3D-printed concrete mixes [6]. Experimental results showed that silica fume incorporation enhanced the fresh concrete performance, while polypropylene fiber addition had limited effect.

Summarizing the literature, it is clear that the rheological properties of 3D-printed concrete can be evaluated in numerous techniques. However, limited work has investigated the relationship between the properties of concrete that is conventionally cast into cubic molds and those of 3D-printed equivalents. Accordingly, this research aims to examine the performance of fresh and hardened 3D-printed and conventionally cast concrete. Mixes were made with desert dune sand, cement, fly ash, and silica fume. The use of dune sand has great potential to replace natural crushed stone and promote sustainable development, evidenced by other work that incorporated dune sand in conventionally cast concrete mixes [7–11]. A control mix with crushed dolomitic limestone aggregates served as a reference. Concrete was tested in its fresh state for slump flow and pumpability and in its hardened state (3, 7, and 28 days) for compressive strength. The effect of mixture proportioning on the experimental results was discussed. Analytical models were developed to correlate the properties of conventionally cast and 3D-printed concrete mixes.

2 Materials and Methods

2.1 Materials

Type I ordinary Portland cement (OPC), class F fly ash (FA), and silica fume (SF) were employed in this work. Their specific gravities were 3.15, 2.32, and 2.23, respectively. Crushed dolomitic limestone (CS) and desert dune sand (DS) served as fine aggregates. Their water absorption was 0.5 and 1.5%, by mass. The chemical composition and particle size distribution of the as-received materials are shown in Table 1 and Fig. 1, respectively. The corresponding unit weight of cement, fly ash, silica fume, and dune sand were 1440, 1262, 1670 and 1663 kg/m³. A polycarboxylic ether polymer-based high range water reducer (HRWR) or superplasticizer (SP) was also used to enhance the workability of produced concrete.

Table 1. Chemical composition of as-received materials.

Component (%)	Cement	Fly ash	Silica fume	Dune sand	Limestone
SiO ₂	19.0	48.0	92.0	64.9	1.1
Al ₂ O ₃	4.5	23.1	1.8	3.0	0.0
Fe ₂ O ₃	2.1	12.5	1.9	0.7	0.1
CaO	66.2	3.3	0.5	14.1	55.2
MgO	1.8	1.5	0.7	1.3	0.0
Na ₂ O	0.1	0.0	0.4	0.4	0.0
K ₂ O	0.6	0.0	1.3	1.1	0.0
LOI	1.5	1.1	1.0	0.0	43.7
Others	4.2	10.5	0.4	15.5	0.0

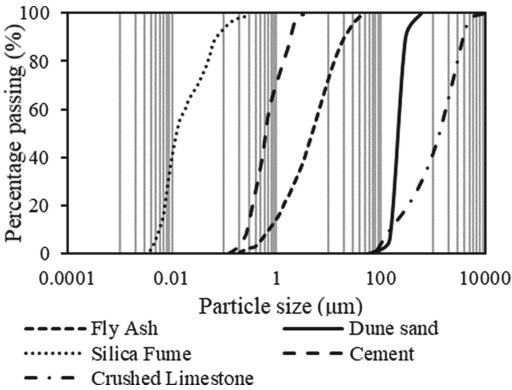


Fig. 1. Particle size distribution of as-received materials.

2.2 Concrete Mixture Proportions

A total of twenty-one (21) concrete mixes were designed following the design methodology of ACI 211.1 [12]. Table 2 summarizes the concrete mixes under investigation. Blends are designated based on the changes to the original control mix, C100-CS, which is made with 100% cement, 100% crushed limestone, water-to-binder ratio of 0.35, and no superplasticizer. The first group of mixes investigated the effect of replacing crushed limestone by dune sand. These are designated as C100-DSx, where x represents the dune sand replacement percentage. A second group examined the influence of adding superplasticizer and is designated as C100-DS100+y, where y is the percent of superplasticizer added. Furthermore, the replacement of cement by fly ash was also studied in mixes C90F10, C80F20, and C70F30. These mixes, along with all those that remain, were made with 100% dune sand. Different quantities of superplasticizer were also added to mix C70F30. The effect of replacing cement by fly ash and silica fume was examined through mix C70F20SF10. Earlier trial mixes made with cement and silica fume only were inferior to those that incorporated fly ash.

As such, they were excluded from this work. A final parameter, in the form of the water-to-binder, was studied with values ranging from 0.35 to 0.40 (C70F20SF10+2SP+w0.38 and C70F20SF10+2SP+w0.40) (Table 2).

Table 2. Mixture proportions of concrete mixes.

Mix designation	Mixture proportions (kg/m ³)							
	Cement	FA	SF	DS	CS	Water	SP	Total
C100-DS0	625.0	0.0	0.0	0.0	937.5	218.8	0.0	1781.3
C100-DS20	625.0	0.0	0.0	187.5	750.0	218.8	0.0	1781.3
C100-DS40	625.0	0.0	0.0	375.0	562.5	218.8	0.0	1781.3
C100-DS60	625.0	0.0	0.0	562.5	375.0	218.8	0.0	1781.3
C100-DS80	625.0	0.0	0.0	750.0	187.5	218.8	0.0	1781.3
C100-DS100	625.0	0.0	0.0	937.5	0.0	218.8	0.0	1781.3
C100-DS100+1SP	625.0	0.0	0.0	937.5	0.0	218.8	6.3	1787.5
C100-DS100+2SP	625.0	0.0	0.0	937.5	0.0	218.8	12.5	1793.8
C100-DS100+3SP	625.0	0.0	0.0	937.5	0.0	218.8	18.8	1800.0
C90F10	562.5	62.5	0.0	937.5	0.0	218.8	0.0	1781.3
C80F20	562.5	62.5	0.0	937.5	0.0	218.8	0.0	1781.3
C70F30	437.5	187.5	0.0	937.5	0.0	218.8	0.0	1781.3
C70F30+1SP	437.5	187.5	0.0	937.5	0.0	218.8	6.3	1787.5
C70F30+2SP	437.5	187.5	0.0	937.5	0.0	218.8	12.5	1793.8
C70F30+3SP	437.5	187.5	0.0	937.5	0.0	218.8	18.8	1800.0
C70F20SF10	437.5	125.0	62.5	937.5	0.0	218.8	0.0	1781.3
C70F20SF10+1SP	437.5	125.0	62.5	937.5	0.0	218.8	6.3	1787.5
C70F20SF10+2SP	437.5	125.0	62.5	937.5	0.0	218.8	12.5	1793.8
C70F20SF10+3SP	437.5	125.0	62.5	937.5	0.0	218.8	18.8	1800.0
C70F20SF10+2SP+w0.38	437.5	125.0	62.5	937.5	0.0	234.4	12.5	1809.4
C70F20SF10+2SP+w0.40	437.5	125.0	62.5	937.5	0.0	250.0	12.5	1825.0

2.3 Sample Preparation

Concrete samples were 3D-printed or cast in the laboratory under controlled ambient conditions (temperature of 24 ± 2 °C and relative humidity of $50 \pm 5\%$). The binding materials, including cement, fly ash, and silica fume, were mixed for 3 min in a pan mixer with saturated surface dry (SSD) aggregates, i.e., crushed limestone and dune sand, as per the mixture proportions of Table 2. The water required to attain the specified water-to-binder ratio was mixed with the superplasticizer, when available. Then, the wet components were added gradually to the dry ingredients and mixed for another 3 min to obtain a homogeneous mixture. Freshly-mixed concrete was separated for two sample casting methods. The first method entailed loading a pumping gun, having a 20×20 mm nozzle, with fresh concrete for 3D printing. Such concrete was then extruded at a flow rate of 2 L/min and printed at a speed of 20 mm/s following a

bidirectional layered pattern, as shown in Fig. 2. The process was repeated ten times, i.e. 10-mm layer each time, to form a 100-mm concrete cube for compressive strength testing. The pump speed was adjusted for every mix to ensure that they are being extruded at a similar rate of 2 L/min. The other preparation method involved casting fresh concrete in two layers in 100 mm cubes and compacting on a vibrating table. Specimens prepared in either method were then covered with a plastic sheet, left to rest at ambient conditions for 24 h, demolded, and placed in a water tank until testing age.

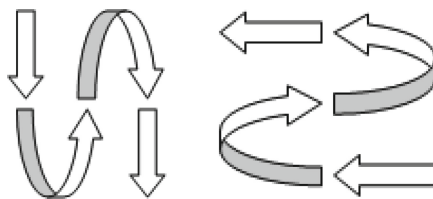


Fig. 2. Bidirectional layered pattern used in 3D-printed concrete

2.4 Performance Evaluation

The rheological properties of fresh concrete were evaluated using slump flow, as per ASTM C230 [13] and pumpability, as suggested by Tay et al. [5]. For conventional concrete, a more substantial flow (in mm) indicated a more workability concrete mix. For 3D-printed concrete, pumpability characterized the concrete's rate of movement from the pump to the nozzle. The pumpability was determined by first measuring the weight of the mix being delivered through the pump at 2890 rpm for 30 s and then, dividing this weight by the density to calculate the flow rate in volume per second (ml/s).

Hardened concrete properties were measured for concrete samples prepared following the two casting methods. 3D-printed concrete cubes were tested for compressive strength at the age of 3, 7, and 28 days, while conventionally cast equivalents were tested at 28 days, according to BS EN 12390-3 [14]. To obtain an average result for each test, three specimens per mix were tested.

3 Results and Discussion

3.1 Slump Flow and Pumpability

Slump flow and pumpability of concrete mixes with crushed limestone being replaced by 0 to 100% dune sand, by mass, is shown in Fig. 3a. Slump flow ranged between 50 and 89 mm, while pumpability varied between 24 and 28 ml/s. Clearly, an increase in dune sand content resulted in a reduction in slump flow and pumpability. In fact, they decreased by an average of 10 and 3% for every 20% crushed limestone replaced by dune sand, respectively. This loss of workability is primarily owed to a larger surface area, more fine particles, and more adsorbed layer water [15].

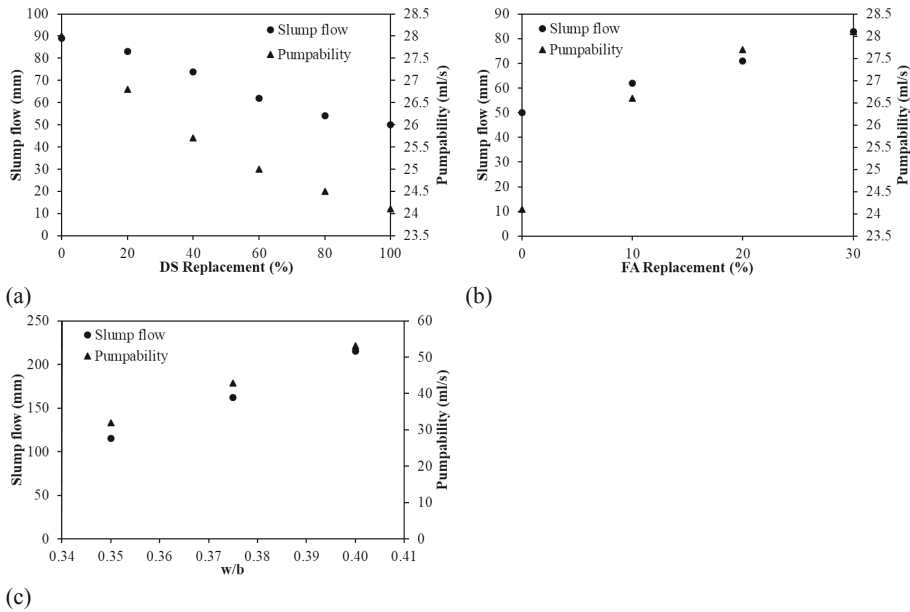


Fig. 3. Slump flow and pumpability index of concrete as a function of (a) dune sand replacement (b) fly ash replacement and (c) water-to-binder ratio

Figure 3b presents the effect of fly ash replacement on the slump flow and pumpability. An increase in slump flow from 50 to 83 mm was noted, while a rise from 24 to 28 ml/s was observed in pumpability. Clearly, fly ash replacement had a positive impact on the workability, owing to the spherical fly ash particles that caused a reduction in friction between the different concrete components' particles. In this regard, it is worth noting that slump flow increased at a near-linear rate of 18%, on average, for every 10% of cement replaced by fly ash. In comparison, pumpability was mostly affected by 10% fly ash replacement (10% increase); much lesser improvements were noted with 20 and 30% replacement values.

The water-to-binder ratio (w/b) was also varied from 0.35 to 0.40. Figure 3c shows the change in slump flow and pumpability with w/b. The values of the former property ranged between 115 and 215 mm, while those of the latter were between 32 and 53 ml/s. It is clear that a higher w/b ratio improved workability. Slump flow and pumpability increased by an average of 36 and 29% for every 0.025 increase in w/b ratio, respectively.

The influence of superplasticizer on the slump flow of concrete made with different binders, i.e. C100-DS, C70F30, and C70F30SF10, is highlighted in Fig. 4a. It first should be noted that changing the binder by incorporating 30% fly ash and then 20% fly ash with 10% silica fume caused a 66 and 36% increase in slump flow. A similar, yet less significant, effect was noted in mixes with a superplasticizer. Apparently, the addition of a superplasticizer could enhance the workability of cement-based concrete

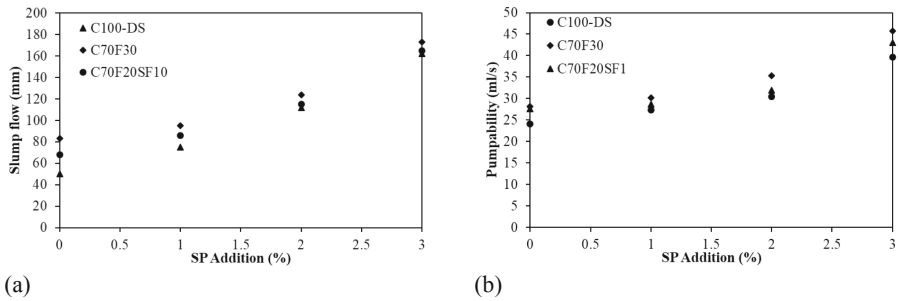


Fig. 4. (a) Slump flow and (b) pumpability of concrete as a function of superplasticizer addition

mixes to be comparable to those that incorporated fly ash and silica fume. In fact, the slump flow increased by an average of 33 mm (37%) for every 1% SP added.

The pumpability of the same concrete mixes is presented in Fig. 4b. The replacement of cement by fly ash and silica fume (C70F30 and C70F20SF10) resulted in an average 15% higher pumpability. Further, the addition of superplasticizer enhanced the pumpability by 5 ml/s (17%) for every 1% SP added.

A comparison between pumpability and slump flow results shows a relation between the two rheological properties. Figure 5 presents a linear correlation that relates pumpability to slump flow. Using Eq. (1), it is possible to predict pumpability (in ml/s) of a concrete mix from its slump flow (in mm) with high accuracy ($R^2 = 0.97$).

$$\text{Pumpability} = 0.173 * \text{slump flow} + 14.09 \quad (1)$$

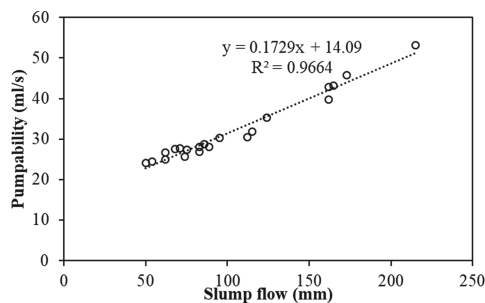


Fig. 5. Relationship between pumpability and slump flow

3.2 Compressive Strength

The compressive strength of 3D-printed concrete cubes was measured at the age of 3, 7, and 28 days. The effect of replacing crushed limestone by dune sand (0 to 100%) is shown in Fig. 6a. As the trend of the results at different ages is similar, the main focus in this work will be on the 28-day compressive strength. Accordingly, it was found that 20% of dune sand replacement increased the strength from 63 to 65 MPa, representing

a 3% increase. It seems that such dune sand incorporation resulted in better particle packing and denser concrete [15]. Nevertheless, higher replacement percentages caused a decrease in strength. In fact, a 2 MPa (3%) decrease was noted for every 10% dune sand replacement subsequently. This is owed to the larger surface area and finer particles of the dune sand, which requires a more binding paste to ensure a proper bond with the aggregates while retaining concrete mechanical properties.

Figure 6b presents the compressive strength of concrete mixes made with different fly ash replacement percentages. Results for 3 and 7-day testing showed that the addition of fly ash had a slightly detrimental effect, owing to a possible delayed pozzolanic reaction. On the other hand, a higher 28-day strength was recorded as more fly ash was added to the mix. This increase was on the order 3 MPa (4%) for every 10% cement replaced by fly ash, owing to its pozzolanic properties.

The effect of increasing the water-to-binder ratio on the compressive strength of concrete is displayed in Fig. 6c. Whether at 3, 7, or 28 days, a strength loss was noted as more water was incorporated into the mix. Across these days, the average reduction in strength was, on average, 10% per 0.025 increase in w/b.

Superplasticizer was added in three proportions (1, 2, and 3%) to three different concrete mixes, namely 100C-DS, 70C30F, and 70C20F10SF. Figure 6d demonstrates the compressive strength at the ages of 3, 7, and 28 days. It is clear that the addition of superplasticizer did not have a significant impact on the strengths of all ages (1% increase). In fact, it was mainly introduced to enhance workability.

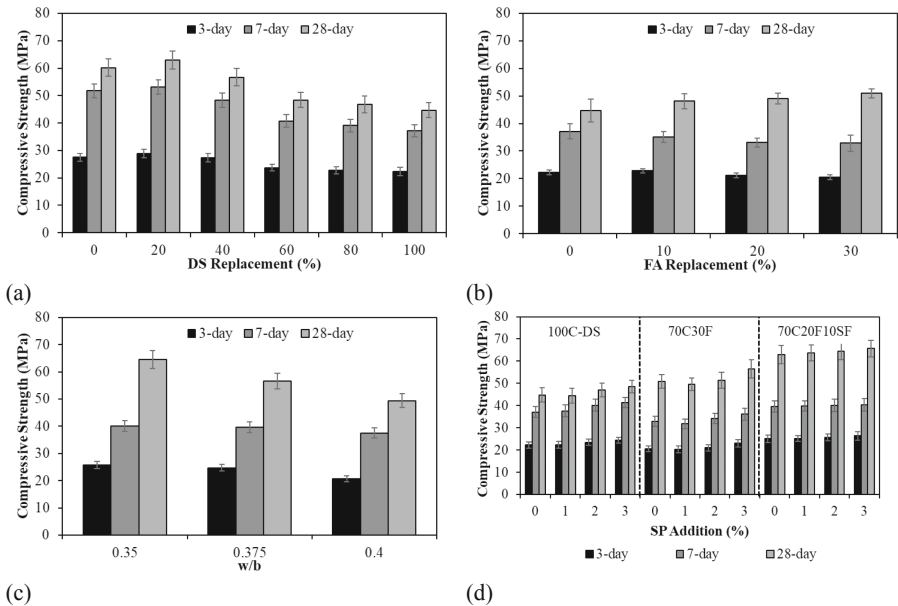


Fig. 6. Compressive strength development of concrete as a function of (a) dune sand replacement, (b) fly ash replacement, (c) water-to-binder ratio, and (d) SP addition.

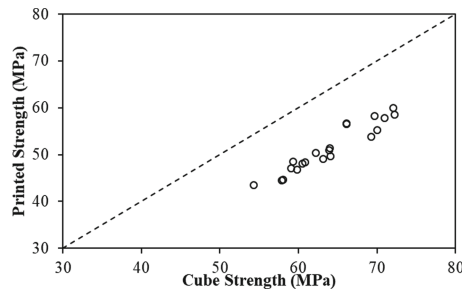


Fig. 7. Printed versus cube strength of 28-day concrete

Nevertheless, the results of Fig. 6d show that the replacement of cement by 30% fly ash and then by 20% fly ash and silica fume affected the compressive strength. A decrease in 3 and 7-day strength of 8 and 13%, on average, was noted when cement was replaced by 30% fly ash. In comparison, an average increase of 11 and 4% was found when cement was substituted by 20% fly ash and 10% silica fume. Clearly, the incorporation of silica fume and fly ash into the mix was more effective at an early age than adding fly ash only. The 28-day compressive strength testing presented different findings. The two replacement schemes resulted in an average of 13 and 39% increase in compressive strength.

Compressive strength was measured for 3D-printed concrete cubes and conventionally cast counterparts. The results of 28-day compressive strength testing are shown in Fig. 7. The strength of conventionally cast concrete cubes was 15 to 25% (average of 22%) higher than that of 3D-printed counterparts. This is due to the denser structure of the former after compaction on a vibrating table compared to the latter, which did not undergo any form of compaction. Nevertheless, analytical models were developed to correlate these two strength results (in MPa) in the form of Eqs. (2) and (3). The main difference between these two equations is the addition of the intercept, which increases the correlation coefficient, R^2 . Accordingly, it is possible to predict the 28-day compressive strength of 3D-printed cubes from conventionally cast cubes with reasonable accuracy.

$$3D\text{--}printed\ strength = 0.93 * cube\ strength - 8.16, R^2 = 0.91 \quad (2)$$

$$3D\text{--}printed\ strength = 0.80 * cube\ strength, R^2 = 0.89 \quad (3)$$

4 Conclusions

This study investigated the properties of 3D-printed and conventionally cast concrete made with dune sand, cement, fly ash, and silica fume. Fresh concrete workability, characterized by slump flow and pumpability, decreased as crushed limestone was replaced by dune sand. However, they could be increased by the replacement of cement by fly ash, addition of a superplasticizer, or increase in water-to-binder ratio. Slump flow and pumpability of concrete mixes were found to be correlated in the form of a

linear equation. The effect of mixture proportions on the 3, 7, and 28-day compressive strength of 3D-printed concrete was also studied. Experimental results showed a decrease in strength with dune sand replacement. Yet, this adverse effect was countered by the addition of fly ash and silica fume. Also, an analytical model was developed to correlate the 28-day strength of 3D-printed concrete to that of the conventionally cast counterparts. Research findings serve as guidelines to produce optimal mixes for large-scale 3D-printed concrete while also introducing a means of predicting its pumpability and compressive strength from conventional concrete.

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An Experimental Testing Procedure to Assess the Buildability Performance of 3D Printed Concrete Elements

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Abstract. Digital fabrication of concrete products represents a breakthrough in the field of civil engineering, revolutionizing the way of conceiving and create architectural/structural elements. Being a new technology, the designers have very few tools to predict and control the time dependent structural response of printed concrete elements, either during and after the production process; furthermore, no testing guidelines exist yet in this specific field. An experimental testing procedure is herein presented to establish the buildability performances of 3D printed concrete elements as a function of the printing layout (e.g. single layer width or thickness). Based on experimental outcomes of uniaxial compression tests performed on cylindrical sample of fresh printable mortar, an analytical model is adopted to estimate the maximum number of concrete layers which can be stacked during a generic printing process before the failure; plastic yielding in compression and self-buckling failure modes are considered to this aim.

Keywords: 3D concrete printing · Buildability · Analytical model · Failure prediction · Fresh properties

1 Introduction

3D Concrete Printing (3DCP) technology belongs to the more general digital fabrication methods utilizing concrete, which allow to efficiently and quickly obtain architectural and structural elements. The main advantages of these technologies are mostly linked to the use of automatic/robotic systems, which make available a full control of the production process. In detail, the layered extrusion process (i.e. 3D concrete printing [1]) consists in the fresh mortar filament deposition, one on the other, up to obtain the designed shape of the concrete element. In order to have a successful printing process, there are many rheological and mechanical requirements that the fresh material must satisfied [2]. Indeed, the concrete material must guarantee the so called “printability”, which includes the pumpability, extrudability and buildability requirements. Consequently, a full characterization of the early age printable mortar is essential for the printing process design.

In this context, the present work describes an experimental testing procedure to assess the buildability performances of 3D printed concrete elements. The first step was the mechanical characterization of the fresh printable mortar (a cementitious mortar supplied by Italcementi) by means uniaxial compression tests: stress-strain laws were obtained as a function of the curing time. The testing procedures were conceived in order to have the minimal sample disturbance, being the tested material in a fresh state, following a similar procedure adopted by the authors in [3]. Subsequently, the outcomes of the uniaxial compression tests (i.e. the temporal evolution of the compressive strength and Young's modulus) carried out on cylindrical samples were used to analytically predict the maximum layers number which can be stacked during the printing process. In particular, the two main collapse modes were considered: the elastic self-buckling and the plastic yielding in compression. Finally, an experimental printing tests were carried out to compare the experimental results with the analytical failure prediction. To this scope, linear geometry samples (i.e. straight concrete walls) were printed up to the collapse, by varying the layer aspect ratio (e.g. single layer width). The authors would like to point out that the geometry examined is the most critical in terms of stability.

2 Materials and Methods

The experimental testing program was designed in order to define the time evolution of the stress-strain law for an additive manufacturing cementitious formulation developed by Italcementi. Uniaxial compression tests (see Fig. 1) were performed at different values of the concrete age, i.e. $t = 0, 10, 20$ and 30 min. The reference time $t = 0$ was the shortest time, about 6 min, necessary to starting the test (taking into account the sample preparation). The time evolution of compressive strength and elastic modulus were obtained by means linear regression of the experimental data. As aforementioned, such time-dependent laws were employed to predict the collapse during the printing of a straight printed wall. In order to validate the analytical prediction, the authors performed different printing tests and the maximum number of stacked layers was recorded. For the printing session, an ABB robotic arm (IRB6700) was used, while the m-tec duo mix 2000 mixer was used to mix and pump the material into the system, up to the nozzle.

2.1 Uniaxial Compression Test

Uniaxial compression tests were performed at room temperature (i.e. $20\text{ }^{\circ}\text{C}$) on cylindrical samples, with a diameter of 60 mm and a height of 120 mm. This geometry was chosen to exclude size effects due to particle size distribution and to ensure that $h/d = 2$, allowing for diagonal shear failure. For the sample preparation a procedure similar to that used in [3] was adopted. The tests were carried out in displacement control, with a value of displacement rate (indicated as "DR" below) of 30 mm/min. Such rate was within the displacement-rate range that is currently used to test printable mortar [4, 5], being high enough to prevent the curing of the fresh material during the test execution. The mechanical response was investigated at different value of the resting time: 0, 10, 20, 30 min (as aforementioned the time $t = 0$ was counted from the end of the sample preparation, about 6 min after the mixing). The testing machine used

was the MTS electromechanical Universal Testing Machine with a 1kN capacity (a picture of the testing set-up was reported in Fig. 1). The force – displacement testing output was converted in a stress- strain law. In detail, the normal stress was obtained by dividing the machine recorded force for the updated cross sectional area, which was assessed according to ASTM D2166/D2166M [6], while the strain was obtained by dividing the displacement of the loading head for the initial value of the sample height. For every sample, three specimens were prepared, in order to obtain an average value of the mechanical properties, and a measurement of the standard deviation. The elastic modulus value was obtained as secant modulus in the 0–5% strain range, that identified the elastic limit behaviour, while the compressive strength value was obtained as the peak stress value. Each sample is identified by the acronym “Txx-Syy”, where: “Txx” represents the resting time of the sample, and “Syy” indicates the sample number. A summary of tests performed was reported in Table 1.

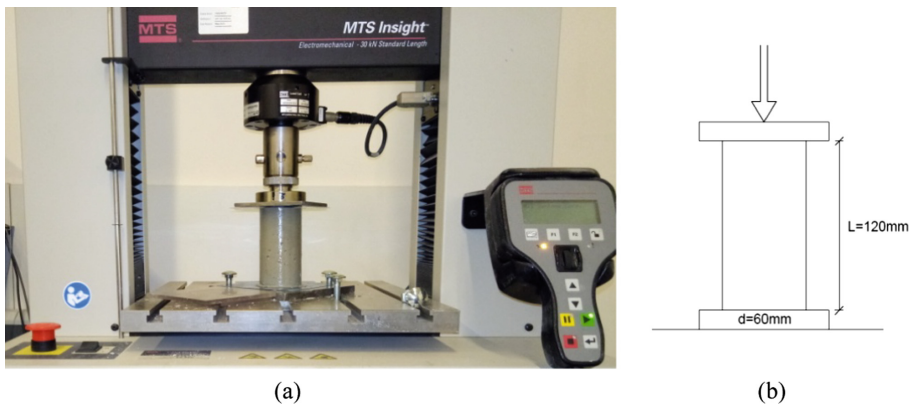


Fig. 1. Machine load MTS, testing set-up (a) and specimen sizes (b)

Table 1. Table test matrix

Displacement rate [mm/min] - (DR)	Concrete age [min] – (T)	Number of samples [-] – (S)	Acronym	Total number of samples [-]
30	0	3	T0-S1; T0-S2; T0-S3	12
	10	3	T10-S1; T10-S2; T10-S3	
	20	3	T20-S1; T20-S2; T20-S3	
	30	3	T30-S1; T30-S2; T30-S3	

2.2 Analytical Failure Prediction

The main advantage of the 3D printing technology is the capability to efficiently and quickly obtain architectural and structural element, of every shape, without formwork. Such aspect implies that the just deposited layers of fresh materials must be able to carry their own weight and that of the layers above them. So, the fresh material must have enough strength and stiffness in order to avoid the premature collapse and excessive deformation during the production printing process. Concerning the failure, only two of the main failure modes were considered: (i) the elastic self-buckling of the whole printed element and (ii) the plastic yielding in compression of the most loaded layer (i.e. the first layer deposited). Other failure mechanisms may take into account the yield stress value of the fresh material or the shear – compression interaction [4]. The critical value of the height for self-buckling depends on more parameters, such as the elastic modulus, the momentum of inertia of the section and the boundary conditions. A simplified formula for the maximum height “ H_{crit} ” assessment due to the self-buckling failure was provided by Greenhill [7]:

$$H_{crit}(t) = (7.83 E(t) I_{min} / \rho g A)^{1/3} \quad (1)$$

where: $E(t)$ is the time evolution of the Young’s modulus; I_{min} is the minimum moment of inertia (depending on the shape of the printed element); A is the cross-section area; and ρ is the density of the material. For the simple geometry of straight wall, the Eq. (1) becomes:

$$H_{crit}(t) = (0.65 E(t) \delta^2 / \rho g)^{1/3} \quad (2)$$

Where δ is the wall width. From the Eq. (2) it is possible to obtain the critical value of the elastic modulus $E_{crit}(t)$ in function of the updated height $H(t)$. The stability check was conducted using the comparison between the elastic modulus and its critical value $E_{crit}(t)$:

$$E(t) < E_{crit}(t) = 0.65^{-1} H^3(t) \rho g / \delta^2 \quad (3)$$

Concerning the plastic collapse in compression, the check was made by comparing the vertical stress $\sigma_v(t)$ and compression strength $\sigma_{c,max}(t)$ for every step of deposition, supposed instant.

$$\sigma_v(t) = H(t) \rho g \geq \sigma_{c,max}(t) \quad (4)$$

The collapse is reached when the Eqs. (3), (4) are satisfied. The maximum numbers of stacked layers may be obtained by dividing the maximum height for the height of single layer. The temporal laws of the elastic modulus and compressive strength were obtained by fitting the experimental data related to each curing time investigated, through a linear regression.

Table 2. Printing parameters adopted

Wall width δ [mm]	Layer height h [mm]	Aspect ratio h/δ [-]	Building Rate BR [mm/sec]
30, 35, 40	10	0.33, 0.29, 0.25	4.2–7

For the analytical failure prediction, the simple geometry of straight wall was chosen. Furthermore, three different width values of the individual layer were examined, in order to assess the effect on the whole element stability. In particular, assuming a constant value of mortar flow from the nozzle, the different width value “ δ ” was ideally obtained by varying the linear printing speed, and then also the building rate (indicated as “BR” below). Such hypothesis is necessary to simulate the same stacking mode adopted in the printing tests, which were subsequently performed as validation of the analytical prevision. The printing parameters adopted for this study were reported in Table 2.

2.3 Printing Test

The experimental validation of the analytical results was performed with the printing set up of Fig. 2. The fresh mortar was mixed and pumped into the system with the mixer-pump m-tec duo mix 2000. The printing nozzle was attached to the robotic arm (IRB 6700) produced by ABB. Since the experimental printing test was used as validation of the above analytical failure prediction, the printing parameters adopted were the same of Table 2. The printing of each sample was carried out by stacking the concrete filament one on the other up to the failure. The wall width (i.e. the layer width) has been varied in order to study the effect of the layer aspect ratio on the stability of the whole printed element. Three samples were printed, one for each wall width investigated.

**Fig. 2.** Printing station (Robotic arm – ABB IRB6700, and mixer pump m-tec duo mix 2000)

3 Experimental Results

In this section, the stress-strain curves for each sample (see Fig. 3) were reported as a function of the curing time investigated (i.e. 0, 10, 20, 30 min). As expected, there was a transition from plastic to brittle behaviour as the curing process takes place. The comparison between average stress-strain curve for each time investigated was reported in Fig. 4a.

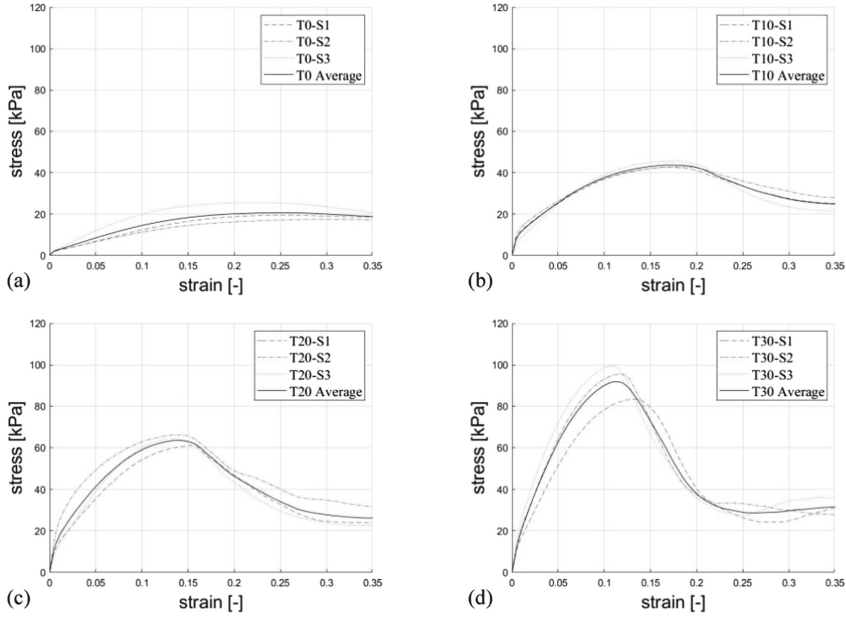


Fig. 3. Stress – strain curve for different concrete age: a) 0 min, b) 10 min, c) 20 min and d) 30 min

The time-dependent laws, Eqs. (5), (6), of the mechanical properties (i.e. elastic modulus and compressive strength) were obtained by linear fitting of the experimental result related to each sample tested (see Fig. 5).

$$E(t) = 82.7 + 28.1 * t \quad (5)$$

$$\sigma_{max}(t) = 19.9 + 2.36 * t \quad (6)$$

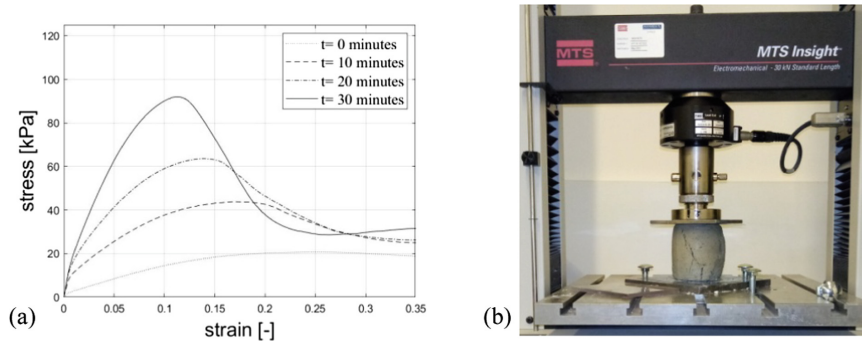


Fig. 4. (a) Stress – strain average curve in function on the concrete age; (b) Failed sample ($t = 10$ min)

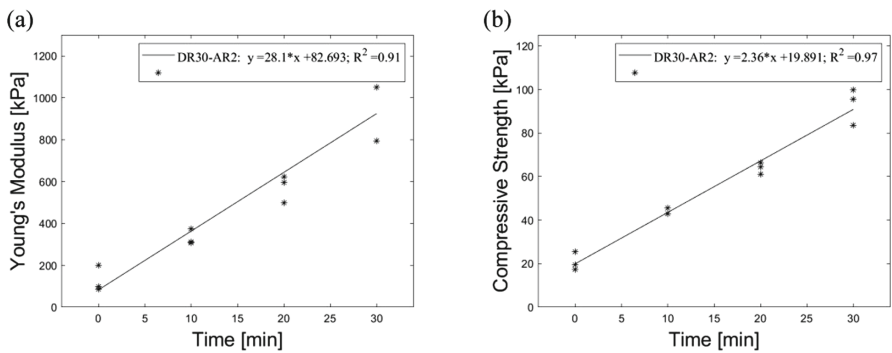


Fig. 5. Linear regression for (a) Young's modulus and (b) Compressive strength

The elastic modulus and the compressive strength were equal to about 82.7 kPa and 19.9 kPa at 0 min and grows up to an average 924.7 kPa and 90.8 kPa at 30 min, respectively.

4 Discussion

4.1 Failure Prediction

The Eqs. (3), (4) were implemented to analytically predict the failure of a printed concrete straight wall. The prediction was made by varying the wall width, in order to evaluate the stability improvement due to increasing value of the resisting cross section and related moment of inertia. The printing parameters adopted for the implementation of the analytical model were reported in Table 2. The width value investigated was equal to 30, 35 and 40 mm. Since the designed width value was achieved by varying the speed of the printing nozzle, the building rate “BR” was varied in the range 4.2–

7 mm/sec. Figure 6 shows the evolution of the: experimentally derived compressive strength (red dashed line) and vertical stress (continuous red line); the experimentally derived Young’s modulus (blue dashed line) and the critical elastic modulus (continuous blue line). For a better representation, the vertical axis is expressed in a semi-logarithmic scale. All the variables (i.e. $\text{semilog}(E)$ and $\text{semilog}(\sigma)$) are reported as a function of the number of stacked layers, “n”, which is linked to the time variable through the following expression:

$$n = t * BR / h_{\text{layer}} \quad (7)$$

where t is the time, expressed in minutes, at which the n-th layer was stacked, BR is the building rate and h_{layer} is the layer height. For brevity, only one of the three diagram n-semilog(E)/semilog(σ) was plotted (Fig. 6), as example.

The intersection between the evolution of the mechanical property and its critical value, provides the maximum number of layers n_{max} . The maximum number of stacked layers was reported in Table 3 for each wall width value.

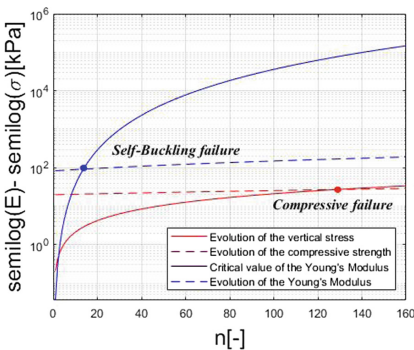


Fig. 6. Comparison between the compressive strength and the vertical stress (red curves) and between the Young’s modulus and the critical elastic modulus (blue curves) [$\delta = 30$ mm]

Table 3. Analytical failure prediction

Wall width δ [mm]	$n_{\text{max,c}}$ (Compression failure)	$n_{\text{max,b}}$ (Self-Buckling failure)	n_{max}
30	128	14	14
35	145	16	16
40	169	18	18

In all cases, the failure was due to the self-buckling. In detail, the maximum number of layers was equal to 14 for a wall width of 30 mm, and it grows to 18 (+30%) for a wall width of 40 mm. Concerning the compressive failure, the maximum number of layers is different for each value of wall width investigated, due to different interlayer time: it is equal to 128 for $T_{\text{interlayer}} = 1.43$ s (i.e. $BR = 7$ mm/sec), while it grows to 169 for $T_{\text{interlayer}} = 2.33$ s (i.e. $BR = 4.2$ mm/sec).

4.2 Printing Test and Validation

The printing tests were performed by means the above robotic station of Fig. 2. Three straight walls 500 mm long were printed (S1, S2 and S3), composed by layers high 10 mm, and different width “ δ ” (i.e. 30, 35 and 40 mm). In order to capture the failure mode, a frontal camera was positioned in the printing station. In Fig. 7 the pictures of the collapse, due to loss of stability, were reported. The maximum height reached for the three samples was 210, 260 and 360 mm (i.e. 21, 26 and 36 layers), respectively for S1, S2 and S3. Going from a width of 30 mm to 40 mm, an increment of about 70% was recorded. Further improvements could be achieved by changing the printing parameters, such as the interlayer time or the geometry. As shown in [8], a significant increment of the maximum number of layers can be achieved by switching from open geometry, as the free wall, to closed geometry, as rectangular wall-layout; indeed, in the first case the printed sample collapsed after 22 layers, while in the second case it collapsed after 33. A comparison between the experimental failure results and analytical collapse prediction was reported in Table 4. The comparison highlights that the analytical prediction underestimates the maximum number of layers, as also happens in other work [2, 8]. The better performance that the printed material exhibited during printing process may be related to:

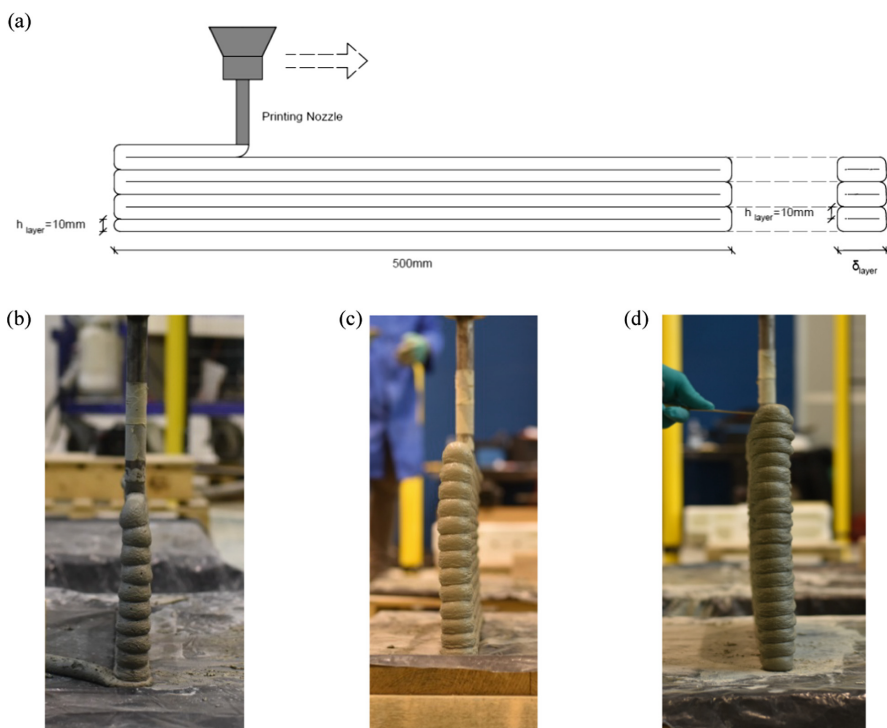


Fig. 7. a) Printing process scheme; Printed samples at failure: b) Sample S1, $\delta = 30$ mm (21 layers), c) Sample S2, $\delta = 35$ mm (26 layers), d) Sample S3, $\delta = 40$ mm (36 layers)

- the high temperatures (of about 35 °C) to which the material is subjected while it is pumped and brought to the printing nozzle;
- the lower porosity degree the printed specimens, which was evident from a qualitative comparison between printed and cast specimens, resulting in higher elastic modulus of compression.
- the transversal bulging effect under the gravity load, that increases the stability of the printed element (the analytical approach does not take into account such phenomenon).

Table 4. Experimental failure results vs Analytical failure prediction

Wall width - δ [mm]	$n_{\max}$ (<i>Analytical prediction</i>)	$n_{\max}$ (<i>Experimental test</i>)
30	14	21
35	16	26
40	18	36

5 Conclusion

In this study, authors presented and discussed the experimental data obtained with uniaxial compression tests performed on early age mortar samples. The outcomes provided the stress-strain laws at different value of the resting time and the time evolution of the mechanical properties (i.e. elastic modulus and compressive strength). Such data are essential for a correct design of the printing process, allowing a simple and quick failure prediction. The experimental printing test data had shown that the failure was reached due to loss of stability of the whole printed element, according to the analytical failure prediction. In particular, the maximum number of layers analytically obtained was underestimated in comparison with that associated to experimental observations. Such underestimation may be correlated to the different physical and mechanical conditions between the cast tested samples and the printed layers. Indeed, the high temperatures (of about 35°C), to which the material is subjected while it is pumped and brought to the printing nozzle, may speed up the curing process. Furthermore, the printed samples had shown a lower porosity degree than cast ones, due to the better material compaction during the pumping. Finally, a further performance improvement may be linked to the layers transversal bulging effect under the gravity load, that increases the stability of the printed element, as well as to the triaxial stress state which may arise within each filament due to the confinement. In order to obtain a more exact failure prediction, it is necessary to implement more accurate analysis (as FEM analysis), which allows to take into account a large number of variables that affect the behaviour of the printed element (i.e. anisotropy, triaxial stress state, etc.).

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Investigation on the Rheological Behavior of Lightweight Foamed Concrete for 3D Printing Applications

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Abstract. Unlike ordinary concrete, lightweight foamed concrete (LWFC) has the benefit of decreasing the self-weight of constructive elements while ensuring an efficient thermal insulation and acoustic absorption as well as high fire resistance. A novel version of LWFC has been recently developed by the authors, with the unique property of “extrudability” in a wide density range, meaning that its production process can be carried out without formworks and exploiting innovative 3D printing technologies. The present contribution is focused on the rheological behaviour of this innovative extrudable LWFC (ELWFC). The rheological behaviour in terms of yield stress of the ELWFC is studied via a rotational rheometer in two different modalities, namely constant shear rate and increasing shear rate. Comparison of the rheological behaviour between ELWFC and classical LWFC is also presented. Additionally, the dimensional stability of the cementitious paste at the fresh state having a given yield stress is assessed through an extrusion test. In particular, the experimental investigation is focused on a target dry density of 800 kg/m^3 , which is identified as a good compromise between insulating features and mechanical strengths. The experimental results show that the considered ELWFC, characterized by a zero slump in the extrusion test, has a yield stress of around 150 Pa (constant shear rate) and 130 Pa (increasing shear rate).

Keywords: Foamed concrete · Lightweight concrete · Concrete 3D printing · Rheological behaviour · Extrusion test · Rheometer

1 Introduction

The emerging and increasing demands for sustainable environment and energy-consumption saving encourage the development of new construction materials in the civil engineering field. Foamed concrete is a kind of special concrete characterized by lightweight properties, cellular microstructure due to the presence of foam that generates air voids, attractive thermal insulation combined with acoustic absorption and fire resistance, especially at the lower densities, as well as good workability [1].

Moreover, it is also made of simple raw materials, namely cement, water, fine sand and possibly additional additives or mineral particles, which makes this material attractive from economic perspectives. Foamed concrete can be employed in the low-to-medium density range as a convenient construction material to realize lightweight panels, infills or internal partitions of buildings, insulating panels for roofs, as filling material of cavities or for geotechnical applications taking full advantage of the aforementioned properties. Obviously, the insulating and lightweight features are improved in the low-to-medium density range, but the mechanical strengths decrease significantly in such range. Therefore, in the relevant literature, different studies have been presented to investigate the main parameters affecting the mechanical strength in such low density range [2, 3], as well as the development of strategies to improve the strength without modifying the density, such as introduction of mineral additions [4], short fibers in the mixture [5, 6], or external grid reinforcement [7]. Other studies focused on the fracture behavior of foamed concrete [8, 9] and on possibility of increasing the fracture energy via the addition of waste micro-particles like biochar [10].

Besides the mechanical strength aspects, an important research field concerns the evaluation of rheological behavior of foamed concrete [11]. Indeed, the rheological behavior influences not only the workability, the pumping, the attitude of the paste to being compacted at the fresh state, but also indirectly affects the hardened properties like shrinkage, durability and mechanical strength. These aspects are even more important when studying novel materials that can be processed via 3D printing technologies. The 3D printing technique has been widely used in several industrial fields like polymers and plastics, and in quite recent times it has been increasingly studied also for concrete materials. The advantages of 3D printing in the construction field are related to the reduction of times, of costs and of disposable elements like formworks and temporary pipes during the different construction phases. As further advantages, 3D printing technique allows the allocation of the material only in those portions of the elements where it is primarily needed, thus allowing a topology optimization of shapes and a significant saving of raw materials. In this context, several studies were recently carried out concerning 3D printing applications with ordinary (normal-weight) concrete [12–14]. However, to the authors' best knowledge, very few studies have been presented with regard to 3D printing of lightweight foamed concrete (LWFC) [15, 16]. In the last few years, a novel kind of LWFC has been developed, studied in terms of mechanical strength and its suitability to be produced via extrusion process [17, 18]. It has been demonstrated that this material, hereinafter called extrudable LWFC (ELWFC), has the peculiar characteristic of keeping its dimensional stability at the fresh state due to the presence of a viscosity enhancing agent (VEA) in the mix. The VEA increases the viscosity and cohesion of the paste at the fresh state. This property is useful to produce lightweight elements in an automated and robotized way through the 3D printing technique, without resorting to traditional formworks. In the development of materials suitable for 3D printing applications, it is of utmost importance to investigate the fresh state properties through rheological measurements. To this aim, this contribution investigates the rheological behavior of this material at a target dry density of 800 kg/m^3 . This density is chosen as a good compromise between insulating features and mechanical strengths. In particular, quantitative evaluations of rheological parameters including yield stress at both constant and increasing shear rate are performed.

Indeed, the yield stress is related to the dimensional stability of ELWFC at the fresh state, which is important for 3D printing applications. Finally, a more direct yet qualitative evaluation of the dimensional stability at the fresh state is also carried out via the extrusion test [17, 18].

2 Materials and Methods

The particular foamed concrete used in this experimental campaign is realized using Portland cement CEM I 52,5 R in accordance with UNI EN 197-1, a water-to-cement ratio of 0.3, preformed foam of density approximately equal to 80 g/L generated with a protein-based foaming agent (trademark name Foamin C) having a concentration of 5% in volume, and a viscosity enhancing agent with concentration of 5% of the cement weight. The foam-to-cement ratio is 0.28. The different ingredients (cement, water and additive) are first mixed for about 1 min, subsequently the necessary quantity of foam is added to obtain the desired target dry density of 800 kg/m³. After around 3 mins of the mixing phase, performed via a vertical mixer with rotational speed of 3000 rpm, the homogeneous cementitious paste is poured in a beaker, as illustrated in Fig. 1 (right). Three different tests were carried out to investigate the rheological properties of the ELWFC paste at the fresh state: 1) evaluation of the yield stress through rotational rheometer RM180 (Fig. 1 – left) at constant shear rate; 2) evaluation of the yield stress at increasing shear rate with the same rheometer; 3) extrusion test. The rheometer RM 180 is a rotational viscometer having compacted dimensions (height equal to 73 cm). The principal features of the rheometer are: precision $\pm 5\%$; applicable torque moment 0.25–7.5 mN $\times$ m, viscosity range 1–10⁶ mPa. All the tests were performed 5 min after the mixing phase is concluded.

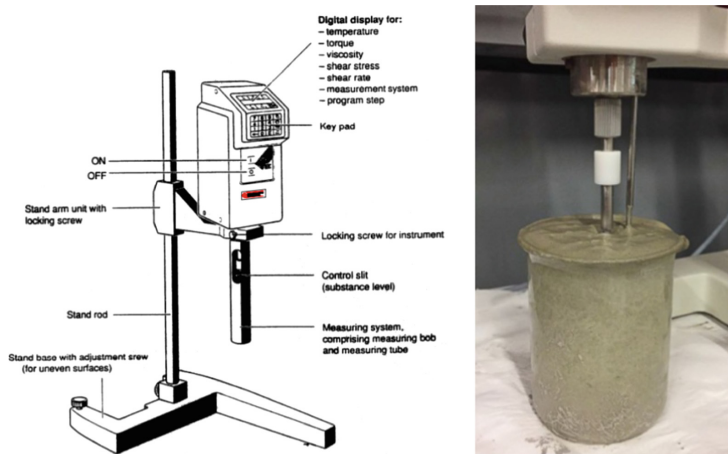


Fig. 1. Rotational rheometer RM 180 used for the rheological characterization of ELWFC (left) and beaker with fresh cementitious paste during the execution of the test (right).

With regard to the rheological characterization of the ELWFC at constant shear rate, the yield stress is identified as the peak shear stress during the test. With regard to the rheological characterization of cementitious materials through tests at increasing shear rate, different empirical rheological models were proposed in the literature. The most famous empirical models are the perfectly plastic model, the Bingham model, the Casson model and the Herschel-Bulkley model. Indeed, different materials may exhibit a different rheological behavior well captured by one of the above-mentioned models, therefore there is no unified constitutive equation applicable to the entire class of cementitious materials. In particular, in this work the Bingham model has been adopted, which is one of the simplest and the most widely used ones. The Bingham model is characterized by the following relationships

$$\tau = G \cdot \gamma \quad (1)$$

$$\tau = \tau_0 + \eta_{pl} \cdot \dot{\gamma} \quad (2)$$

where τ is the shear stress (in [Pa]), $\dot{\gamma}$ (in $[s^{-1}]$) is the shear rate, G (in [Pa]) is the shear modulus, τ_0 (in [Pa]) is the Bingham yield stress, and η_{pl} (in [Pa s]) is the plastic viscosity. Expression (1) applies to cases in which the shear stress is lower than the yield stress, i.e. in the pre-peak branch in which the yield stress is assumed as a linear function of the shear rate. Expression (2), referred to as the ideal Bingham model, applies to cases in which shear stress is higher than the yield stress, and implies a linear relation with the shear rate.

Additionally, to evaluate the dimensional stability of the ELWFC at the fresh state, in particular after 5 mins from the mixing phase, the extrusion test was performed [18]. This test consists in a simulation of a simple extrusion as illustrated in Fig. 2. This test serves to complement the previous quantitative evaluation of the rheological properties of ELWFC through a qualitative measure of the dimensional stability of the paste. The extrusion test is performed on cubic specimens having cross section 5×5 cm and height 4.5 cm. Therefore, the combination of the extrusion test with the corresponding values of the yield stress evaluated through the rheometer serves to identify whether or not a specific yield stress leads to an extrudable paste, i.e. a paste characterized by an excellent dimensional stability such that it can be processed via 3D printing technology.

3 Results and Discussion

In this section, the results concerning the yield stress of ELWFC pastes obtained by the rotational rheometer RM180 are presented. For comparison purposes and to demonstrate the peculiar properties of the ELWFC at the fresh state, the same tests were repeated for classical LWFC characterized by the same target dry density of 800 kg/m^3 and by same water/cement ratio. The rheometer applies an appropriate force able to trigger a laminar flow in a material. In particular, the rotational rheometer used here acts on a material that is preventively cut along a surface. One of the two surfaces is put

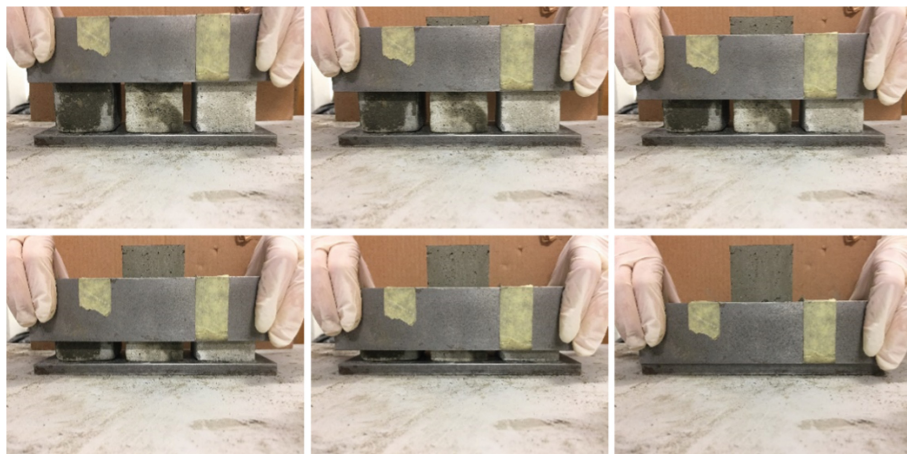


Fig. 2. Sequence of photographs describing the steps of the extrusion test on ELWFC.

in rotation. During the test, the speed rotation and the torque moment can be recorded or imposed. As already said, two types of measurements were carried out.

The first procedure is at constant shear rate of 5 Hz, thus recording the corresponding reaction torque moment on the surface. The second procedure is at increasing shear rate from 0 to 120 Hz.

In the first procedure (constant shear rate), the yield stress is the highest reaction torque moment identified by the rheometer, which represents indeed the maximum shear strength of the material. Stresses higher than this yield stress induce the plastic flowing of the material. In the second procedure, so-called flow curves (shear stress versus shear rate) of the material are obtained, and the resulting interpretation is carried out by means of the Bingham model. Both the studies were carried out on ELWFC pastes at 800 kg/m^3 after 5 mins from the end of the mixing phase. The choice of the shear rate test at 5 Hz is related to the limitations of the testing equipment; such shear rate value does not allow the study of the specimen in the elastic and viscoelastic phase, but only the shear stress. In order to investigate the behavior of the paste in the elastic phase, lower shear rates in the range 0.001–0.1 Hz should be adopted. In Fig. 3 the results of the constant shear rate test are shown. The obtained yield stress for LWFC is around 25 Pa, while the yield stress for ELWFC is six times higher, approximately 150 Pa. It is noted that the test duration is extended well beyond the attainment of the peak shear stress (red circle) identifying the yield stress. As expected, once the yield stress is exceeded, the material still offers a residual shear resistance that is almost constant and approximately equal to 10 Pa and 80 Pa for LWFC and ELWFC, respectively. Moreover, it is noted that for the case of LWFC there are structuring and de-structuring phenomena occurring after the attainment of the yield stress, which are not present in the ELWFC (cf. the two curves in Fig. 3 top and bottom). In the authors' opinion, these phenomena could be visible also in the case of ELWFC for slower shear rate, which are however not compatible with the testing equipment used here.

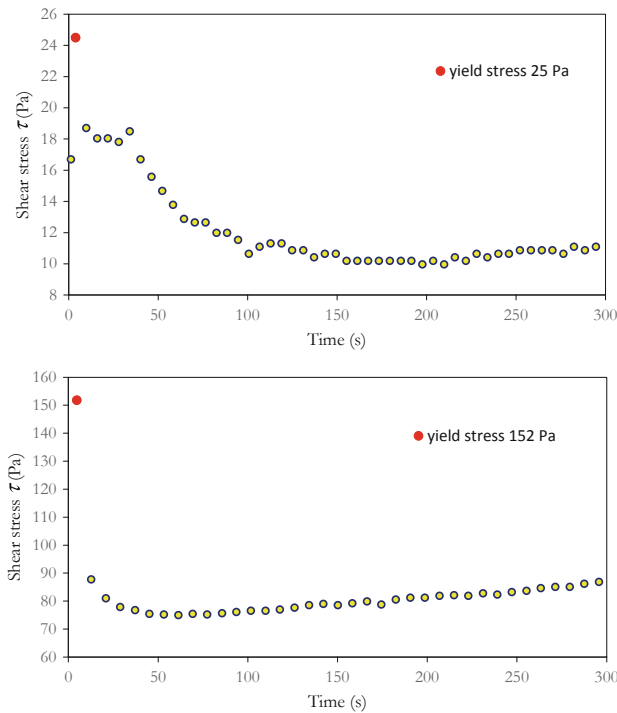


Fig. 3. Results obtained with rheometer at constant shear rate of 5 Hz for LWFC (top) and ELWFC (bottom).

Other two specimens characterized by the same LWFC and ELWFC paste were tested under increasing shear rate to determine the flow curve. The results are reported in Fig. 4. It is noted that the shear stress exhibits an almost linear increase with the shear rate. This suggests adopting the idealized Bingham model, Eq. (2), to interpret the experimental findings, which is superimposed in the plot as a red line. The Bingham yield stress τ_0 evaluated as the intercept of the red line with the vertical axis is again around 25 Pa for LWFC and slightly lower than 130 Pa for ELWFC. Therefore, the yield stress evaluated at increasing shear rate seems to be around 15% lower than that evaluated at constant shear rate for ELWFC, while for LWFC the yield stress is almost the same in the two procedures.

Finally, in order to qualitatively correlate the yield stress results with the ability of the material to keep its dimensional stability at the fresh state, other two specimens, one realized with LWFC and the other with ELWFC, were subjected to the extrusion test after 5 mins from the mixing phase. The results are illustrated in Fig. 5, for a specimen having the same initial dimensions as above ($5 \times 5 \times 4.5$ cm). In this figure, it is clearly shown that the yield stress associated with ELWFC guarantees an excellent dimensional stability, with negligible settlement of the specimen, whereas the LWFC specimen exhibits a pronounced slump and a marked lateral expansion, typical of a material with low consistency.

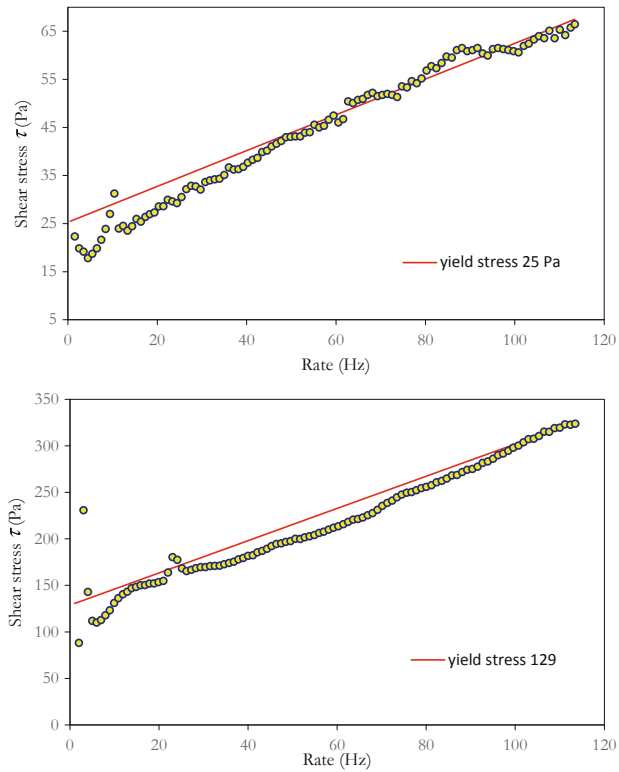


Fig. 4. Results obtained with rheometer at increasing shear rate for LWFC (top) and ELWFC (bottom).

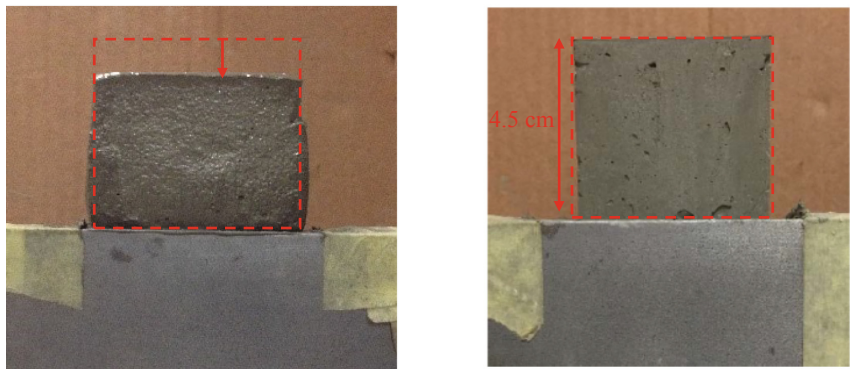


Fig. 5. Excellent dimensional stability evaluated through the extrusion test of LWFC (left) and ELWFC (right).

4 Conclusions

This contribution has presented a preliminary investigation on the rheological properties of extrudable lightweight foamed concrete (ELWFC) in terms of yield stress, evaluated through a rotational rheometer under both constant and increasing shear rate for a target dry density of 800 kg/m^3 . The obtained yield stress, of around 150 Pa and 130 Pa in the two testing procedures, has been compared to the values of analogous specimens made of classical lightweight foamed concrete (LWFC), which shows much lower yield stress values (of around 1/6). The peculiar capability of the ELWFC to keep its dimensional stability at the fresh state has been assessed through an extrusion test at 5 mins from the mixing phase. As expected, the higher yield stress of ELWFC compared to LWFC guarantees an excellent dimensional stability, with negligible slump and lateral expansion. Based on these results, it is possible to conclude that lightweight foamed cementitious pastes characterized by yield stress values of around 130–150 Pa can be defined “extrudable” and can be usefully processed through 3D printing technologies.

The useful extrudability and insulating features of the proposed ELWFC material, characterized by a compressive strength higher than 10 MPa at 800 kg/m^3 , can be exploited in innovative precast plants based on 3D printing production process or printed directly in situ for the realization of lightweight panels to be used as internal partitions, external infills, and suspended ceilings of buildings. The non-structural nature of these elements is certainly an advantage because typical issues concerning the placement of appropriate steel reinforcement in such 3D printed elements can be disregarded.

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Experimental Investigation on the Early Age Tensile Strength of Fiber Reinforced Mortar Used in 3D Concrete Printing

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Abstract. Digital fabrication with cement-based materials requires specific attention to be paid to the rheological and mechanical material properties both in the fresh and hardened state. For the layered extrusion process, the cement-based material needs to satisfy the “printability” requirement. Generally, printable mortars exhibit brittle mechanical behaviour due to the absence of reinforcement. In order to overcome this issue, many different strategies can be implemented. Among them, the addition of short fibers in the mortar represents a first step towards the development of robust materials for 3D printing in construction. In this context, the paper focuses on the early stage tensile properties of fiber-reinforced cement-based material to be used in the layered extrusion process. The embedment of discrete fibers in a printable mix is expected to improve the mechanical behaviour but, at the same time, it implicates a loss of workability in the mix, which could lead to problems during the printing process (in terms of extrudability and pumpability of the mix). In this paper, the mechanical response under direct tensile is investigated as a function of the type/concentration of fibers as well as the mortar resting time. Furthermore, the effect of varying the amount of the superplasticizer to guarantee the printability requirement of the printable mortar is also investigated. In a quality control framework, the development of tensile fracture properties, in the considered production time frame, is fundamental to determine the printability of the mix, with reference not only to the quality of the finishing but also to the speed of the printing process.

Keywords: Fiber-reinforced mortar · Digital fabrication with concrete · Early age properties · Tensile strength

1 Introduction

The study of “very early” and “early” age mechanical performance of cement-based materials is crucial in the development of “printable” mixes for the 3D printing of concrete. The printability of the mix, which is circumscribed by the pumpability, extrudability and buildability, can be characterized by some known mechanical properties like the yield stress and the tensile capacity in the fresh state. Good tensile capacity of the mix ensures lesser probability of breakage of the filament in the extrusion process and also overcomes cracking forces due to shrinkage. The shrinkage cracking is also prominent because of the compatibility restraints between the subsequent layers in the additive manufacturing process. The addition of short fibers to the mix result in a higher tensile capacity in conventional mixes that are not used in printing. This has motivated the need to study the effect of fiber addition into 3D printable mixes on the development of their tensile properties.

Fresh concrete is identified as a Bingham fluid with visco-plastic behavior from Roussel [1]. This means that concrete doesn’t flow till a threshold yield stress is applied. The extrusion process requires a low value of the yield stress for easy printability. However, the yield stress should be high enough to maintain stability under self-weight in the process of additive manufacturing. The direct shear test is an alternative test to traditional rheometric techniques and is widely used in soil mechanics to determine the cohesion C and angle of internal friction ϕ . Wolfs et al. [2] have developed a numerical model to analyse the mechanical behaviour of fresh, 3D printed concrete based on Mohr – Coulomb failure criterion and linear stress strain behaviour up to the failure. The failure criterion was built through experimental results from direct shear tests. In this paper, a special focus is given to the investigation of the tensile strength while the yield strength will be focused on in further work. In particular, the early-age mechanical response under direct tensile is investigated as a function of the type/concentration of fibres as well as the mortar resting time. Furthermore, the effect of varying the amount of the superplasticizer to guarantee the printability requirement of the printable mortar is also investigated.

2 Experimental Design

This paper investigates the very early and early stage tensile capacity of fiber reinforced printable mortars through the experimental setups detailed in [3]. Tensile tests were performed on mortar samples with different concentration and type of fibers at different resting time after casting, namely 30, 60 and 120 min.

2.1 Materials

The mix design of the mortar for the samples developed was adopted from Asprone et al. [4]. The maximum aggregate size in the cementitious mix used was 4 mm to ensure compatibility with the 25 mm nozzles of the printer. The water-binder ratio was maintained at 0.39 and a polycarboxylate superplasticizer was used to ensure the pumpability of the mix. 14 ± 2 mm slump was measured as per the EN 12350-2:2009

corresponding to workability class S1. The reference plain cementitious mix contained 0.12% in volume of non-structural fibers (i.e., Polypropylene short fibers, 18 mm long); in order to study the effect over time of the structural fibers (SF), Polyvinyl Alcohol short fibers (12 mm long) were added to the mix in increasing dosages (i.e., 0.80 and 1.00% in volume). In detail, taking into account the experimental results obtained from Esposito et al. [5], the dosages were varied as follows: 0.00% SF and 0.12% NSF (i.e. reference mix above), 0.80% SF and 0.12% NSF, 1.00% SF and 0.12% NSF. The dosage of SF was higher than the one used in [5]. The superplasticizer (SP) content was varied from 0.08% to 0.13% (by weight of cement) when structural fibers were added to the cementitious mix, in order to ensure the printability requirement (checked via printing test using BIGDELTA WASP).

The SF dosages were chosen in accordance with the minimum required concentration value suggested by Weinlin L. and Jianping H. [6] and Yuexiu W. et al. [7] to observe a structural effect.

2.2 To Study the Effect of Concentration of Superplasticizer

The concentration of superplasticizer used to study the effect of concentration of structural fibers on the tensile strength of cementitious mortar specimen was varied to attain the consistency and the printability of the matrix. The effect of superplasticizer concentration on tensile strength of the cementitious mortar specimen in fresh state was investigated. The direct tensile test was carried out on cementitious matrix (i.e. without fibers) with different value of SP dosage, i.e. 0.08 and 0.13% by weight of cement. The test variables are listed in Table 1.

Table 1. Experimental design showing nomenclature of specimen for various concentration of superplasticizer and time

	t + 30 min	t + 60 min	t + 120 min
SP = 0.08%	30T0.08SP	60T0.08SP	120T0.08SP
SP = 0.13%	30T0.13SP	60T0.13SP	120T0.13SP

2.3 To Study the Effect of Concentration of Structural Fibers

The effect of structural fibers over time was investigated. The test variables are listed in Table 2. All concentrations shown below are expressed in volume ratio (i.e., V/V%).

Table 2. Experimental design showing nomenclature of specimen for various concentration of Structural fibers and time

	t + 30 min	t + 60 min	t + 120 min
NSF = 0.12% + SF = 0.00%	30T0.12NSF + 0.00SF	60T0.12NSF + 0.00SF	120T0.12NSF + 0.00SF
NSF = 0.12% + SF = 0.80%	30T0.12NSF + 0.80SF	60T0.12NSF + 0.80SF	120T0.12NSF + 0.80SF
NSF = 0.12% + SF = 1.00%	30T0.12NSF + 1.00SF	60T0.12NSF + 1.00SF	120T0.12NSF + 1.00SF

3 Experimental Test Setup

The fresh cementitious mortar was poured into a plexiglass box (dimension $332 \times 80 \times 60$ mm) fabricated with two semi-circular protrusions at the center. The placing was done using a spatula and the surface of the mortar specimen was pressed lightly to eliminate air bubbles. No vibrated compaction was done to the specimen. These protrusions contributed to a 32.5% reduction in the cross-section of the specimen therefore a stress concentration during the tensile tests required to predetermine the approximate position of the crack in the specimen. The plexiglass box was made up of two parts, one fixed and the other movable. The tensile force was measured with the help of a load-cell with a 600 N capacity, fitted to the movable part. A constant horizontal displacement rate of 0.01 mm/s was imposed on the mobile part of the box.

The force recorded by the load cell was adjusted considering the rate due to the friction. In detail, the frictional force on the slipping surfaces was estimated equal to about 10 N: such value was the residual force recorded during the test after the complete detachment of the two parts of the specimen (i.e. after specimen failure). Figure 1 (a) and (b) below depict the direct tensile test setup performed on the specimen.

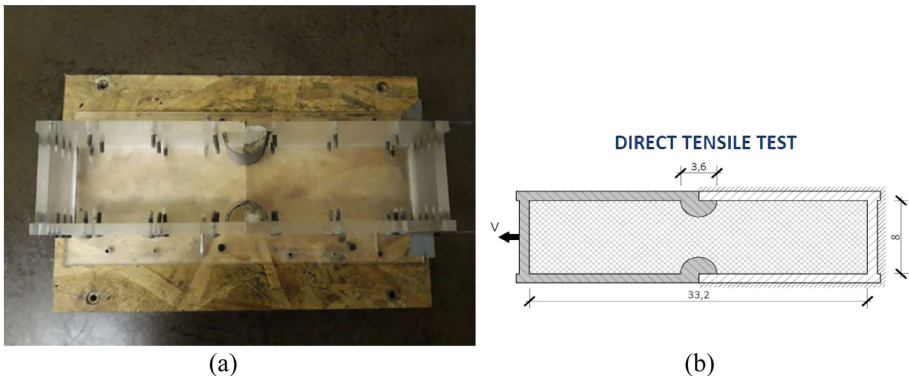


Fig. 1. (a) Tensile test setup and (b) schematic

The tensile stress was calculated by dividing the load recorded on the load cell for the cross-section area at the likely failure region (2640 mm^2 : area of initial cross section passing through the tips of the semi-circular protrusions at the center of the specimen).

4 Experimental Results and Discussions

4.1 Effect of Concentration of Superplasticizer

Figure 2 shows the peak tensile stress (in kPa) vs age (in min) for the investigated cementitious mortars with two different concentrations of the superplasticizer (i.e., 0.08

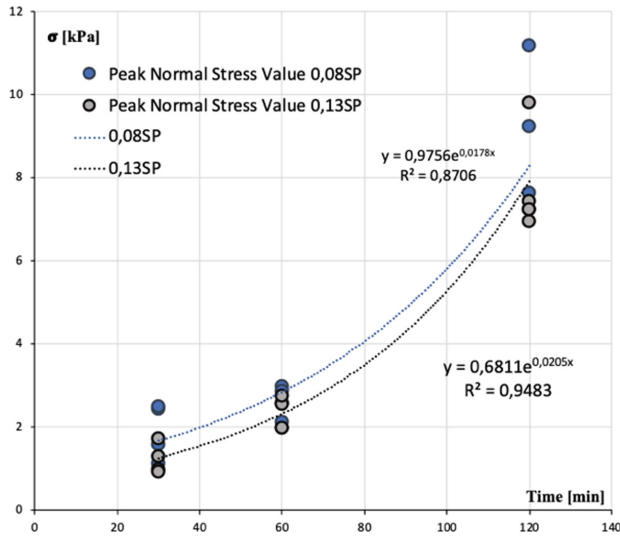


Fig. 2. Tensile strength of early age mortar specimen at various concentrations of the superplasticizer.

and 0.13%). Average peak tensile stress values for both concentrations follow a similar exponential curve with time. The values of the individual tests show that the tensile strength is higher when the concentration of superplasticizer is lower, however the difference in these values are very low and can be ignored in the next part of this study, being included in the experimental scatter.

4.2 Effect of Concentration of Fibers

In Fig. 3 the average peak tensile stress values, recorded for each tested cementitious mix (0.12NSF + 0.00SF, 0.12NSF + 0.80SF and 0.12NSF + 1.00SF), are reported as a function of resting time, i.e. 30, 60 and 120 min. The tensile strength for the reference mix (i.e. 0.12NSF + 0.00SF) is equal to about 2 kPa at 30 min and its value grows up to 15 kPa at 120 min, due to hydration of cement.

For the resting times investigated, the effect of the structural fibers on the mechanical behaviour in tension was negligible; this is probably due to the fresh state of the material that prevents an effective anchoring of the fibers into the mortar.

Instead, the non-structural fibres, usually used to avoid plastic shrinkage cracking, improved the mechanical behaviour at a very early age state. Indeed, by comparing the results of the cementitious matrix and fibro-reinforced mix, respectively plotted in Fig. 2 and Fig. 3, it is possible to observe that the tensile strength increases from 8.2 kPa to 15 kPa (at 120 min), adding non-structural fibers to the mix, while no increment was recorded when structural fibers were also added. Such effect, at very early age state, could be a result of the higher homogenous distribution of polypropylene fibers in the matrix owing to their hydrophilic nature.

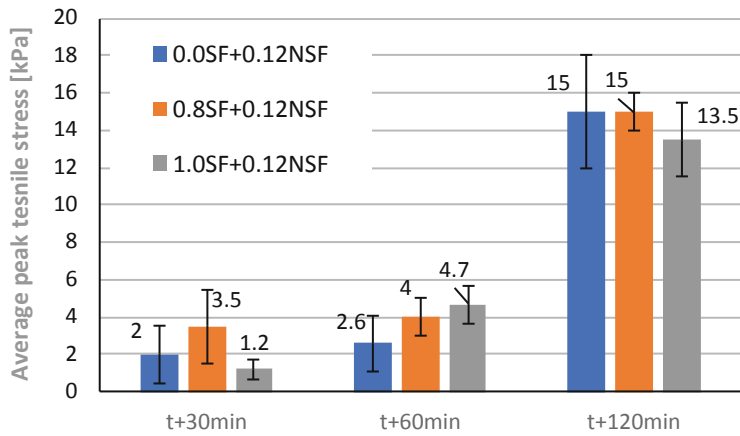


Fig. 3. Average Peak Tensile Stress (kPa) at different concentrations of fibers.

A comparison between the tensile response of fiber reinforced mix and the corresponding cementitious matrix (i.e. 0.12NSF + 1.00SF and 120T0.13SP) is reported in Fig. 4a, in which it is possible to see the double peak of the tensile stress due to the progressive fracture of the specimen (see black curve). Instead, a snapshot of the crack pattern in one of the tested specimens is reported in Fig. 4b.

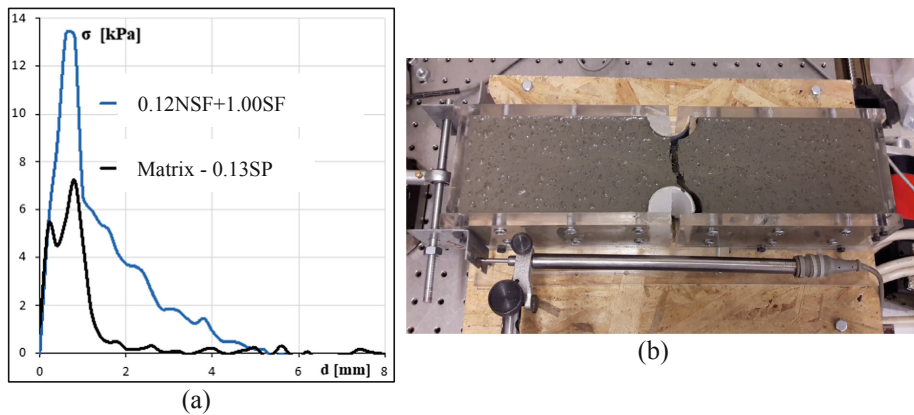


Fig. 4. Example of Stress vs. displacement tensile response of fiber reinforced and plain mortars at 120 min (a) and fractures specimen at the end of tensile test (b)

5 Conclusions

In this paper, the early age properties of printable mortars, reinforced with 0.12% by volume of non-structural polypropylene and different volume concentrations of structural polyvinyl-alcohol fibers (0.00, 0.80 and 1.00% in volume) were studied.

Direct tensile tests were carried out at different value of the resting time (30, 60 and 120 min from casting), in order to define the time evolution of the mechanical behavior. The employed test set-up and methodology, consisting of polycarbonate molds in which concrete is poured just after mixing and then directly tested at a given time duration after casting, has been proven adequate for the purpose of measuring the evolution of very early age tensile fracture properties of printable plain and fiber-reinforced cementitious mortars.

The tests showed that, while surely improving the toughness performance, for the employed fiber volume fraction a tensile softening response is still obtained, with a transition from fluid to solid behavior in a time framework ranging from 30 to 120 min. Furthermore, the experimental campaign showed that:

- Increasing the superplasticizer dosage (from 0.08 to 0.13% by weight of cement) it was possible to add structural PVA fibers (from 0.8 to 1.0% in volume), at the same water/cement ratio. However, the effect of the variation in superplasticizer amount on the mechanical response was negligible, being the strength variation contained in the experimental scatter.
- The non-structural fibers, usually used to avoid plastic shrinkage cracking, improved the mechanical behaviour at a very early age state: the non-structural fibers are more deformable than the SF ones and they better follow the deformation of the surrounding mortar.
- For the resting times investigated, the effect of the structural fibers on the mechanical behaviour in tension was negligible; this is probably due to the fresh state of the material that prevents an effective anchoring of the fibers into the mortar.

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Transition from Fluid to Solid Concrete in the Flexible Mould Process

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Abstract. The transition period between the mixing of concrete and the begin of setting increasingly receives attention, as special production processes can be developed with tailor-made fresh state characteristics. In this publication the two processes of 3D Concrete Printing (3DCP) and the production with the Flexible Mould Process (FMP) are discussed and compared.

The FMP is a relatively new manufacturing method that was developed to allow the efficient production of curved thin concrete panels for cladding or structural use. The term ‘flexible’ refers to the deformation into the required curved shape of both the compliant mould surface and the fresh concrete contained by the mould shortly after casting. After that deformation, both the mould and the concrete are left for further hardening until demoulding is possible. The development of the 3DCP technique progresses fast, hereby new perspectives are gained with regard to mix design, production and structural performance. Sideway, test methods need to be developed or re-evaluated. The early age strength and strain capacity are important parameters for both processes, although they are not the same with regard to magnitude, period or time after mixing. Both processes can be executed within an open window and with specific boundary conditions only. This publication discusses and compares both processes. The implications of these recent findings are translated to practical aspects with regard to the production with the FMP.

Keywords: Flexible mould · 3DCP · Rheological measurement · Concrete production · Self-Compacting concrete

1 Introduction

The behaviour of concrete in the period between mixing and the begin of setting is crucial for the casting execution and the performance during service life (on the material and structural level). Many processes benefit from tailor-made plastic stage characteristics, see Table 1.

Applications mentioned in Table 1 require specific characteristics at the moment of production immediately, within a few minutes or even hours after mixing. The production processes of FMP and 3DCP are special as they define specific boundary conditions at two different moments. Table 2 summarises both production processes.

Studies with regard to the FMP [1–3] are much rarer compared to research executed on 3DCP. Although the main target applications of the FMP are different from 3DCP, it

Table 1. Examples of concrete characteristics in the fresh state dependent on the application.

Consistency aspect	Benefit	Application examples
Very low yield strength	Improves casting rate, eliminates compaction, improved appearance	Prefabricated elements, architectural elements
Very low viscosity	Facilitates concrete placement	Floors, sandwich elements
Moderate yield strength	Casting in a slope	Bridge decks, ramps
Moderate segregation due to compaction	Production benefits, e.g. improved placement and strength of anchors	Prefabricated sandwich elements
Green strength	Demoulding directly after casting	Pipes, hollow-core slabs

Table 2. Comparison of two production processes: 3DCP and FMP.

Process	3DCP	Flexible mould process
Production	Extrusion process	Casting process
Application	3D structures	Thin panels, sandwich elements
Existence of open window	Yes	Yes
Period open window	Very short, dependent on extrusion rate and weight of material layers printed above concrete	Medium, e.g. 45 min dependent on curvature, panel thickness and concrete characteristics
Relevant material characteristics (at different stages)	1) Placing phase: pumpability and printability 2) During printing: buildability	1) Filling phase: Very low yield strength 2) Deformation phase: Sufficiently high yield strength and sufficient strain capacity
Potentially problematic	Collapse (strength, buckling), cracking, overly deforming, bond insufficient between layers	Cracking, deviating panel thickness due to material movements
Shaped by	Extrusion nozzle and material characteristics after extrusion	Mould dimensions, deformed position
Maximum aggregate size	Dependent on nozzle size, typically not larger than 2 mm	Dependent on element thickness, at least 4 mm
Paste content	Mortar-base. Larger time-dependent deformations	Concrete-base, smaller time-dependent deformations

is worth to evaluate the two production processes more in detail. Concrete for the production in the FMP has to be designed for high flowability, whereas 3DCP materials flow only, if they flow at all, in the pumping/feeding and deposition phases. Still, both types of material behave roughly as visco-plastic Bingham materials. The changes of properties in the plastic stage are discussed in the following sections and how they can be related to the requirements for the two different production processes.

2 Boundary Conditions of the Flexible Mould Process

The FMP system for the production of double-curved prefabricated concrete elements was further developed and studied at Delft University of Technology [1]. The production comprises casting of an element in horizontal position and, after a waiting period, the mould is deliberately deformed and positioned on pre-arranged mould supports. An example of mould deformation is shown by Fig. 1.



Fig. 1. Flexible mould system before and after deformation [1].

The element hardens in the deformed mould, which, afterwards, can be re-used for the production of other elements having the same or a different geometry. In the period between mixing and de-moulding, the concrete behaviour changes from a Bingham fluid to a solid state with changing contributions to the yield strength in time of thixotropic structural build-up and progress of hydration. As the applied concrete has a very low yield strength, which is also obtained by the addition of superplasticizer(s), the main contribution to the increase in yield strength in the time until deformation comes from the flocculation of fine particles exerting a thixotropic action [4]; every movement of the mould has to be executed with caution not to unintentionally disturb the structure and reagitate the concrete. Two boundary conditions are:

- 1) Filling phase: In the horizontal position, effective casting is realized by the use of self-compacting concrete (SCC). A very low yield stress is required in order to avoid the compaction energy impact on the potentially fragile mould and to obtain a smooth surface texture;
- 2) Deformation phase: During deformation, 1) the yield stress of concrete has to be sufficiently high to prevent that concrete flows over the edge of the mould (Fig. 2a) and 2) concrete has to retain sufficient strain capacity to prevent that the elongation of the concrete localises in (larger) cracks (Fig. 2b).

The element geometry and applied mix design determine whether the criteria can be fulfilled and if so, what the duration is of the open window for adequate deformation. Dependent on the geometry (curvature, dimensions, slope) of a panel produced with the FMP the open window for deforming the mould can be longer or shorter, different in time after mixing or, in some cases, deforming cannot be realised without cracking.

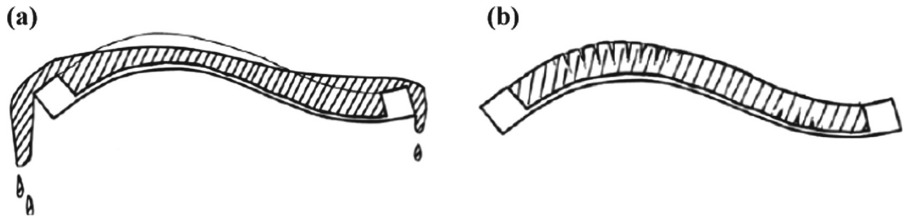


Fig. 2. Two boundary conditions for the mould deformation a) maintaining stability through an adequate yield strength and b) prevention of significant cracking through strain capacity [1].

Critical Yield Strength

Especially, the early phase before setting is very important for the production with the FMP (Fig. 3). The open mould locally can be in a steep slope after the deformation, the concrete then has to support its own weight. The original Eq. (1) (left part), proposed by [5], was applied to calculate the required yield strength for a given slope of concrete and it was extended for the prediction of the yield strength in the FMP (right part of Eq. (1)) [1] in relation to the geometry of a mould with length L and circular shape R after deformation (for a circular mould curvature: $\sin(\theta) = L/2R$).

$$\tau_{0,crit} = \rho \cdot g \cdot h \cdot \sin(\theta) = \rho \cdot g \cdot h \cdot \frac{L}{2R} \quad (1)$$

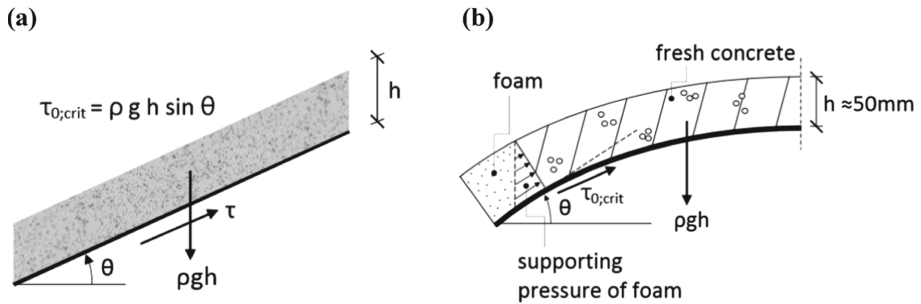


Fig. 3. Critical shear yield strength $\tau_{0,crit}$ of concrete under a slope (a) model proposed by [5] and b) modified model [1].

where:

$\tau_{0,crit}$	Critical yield strength of concrete under slope [Pa]
ρ	Density of the concrete [kg/m^3]
g	Acceleration of gravity [$\text{kg}\cdot\text{m/s}^2$]
θ	Slope angle [rad]
$L/R/h$	Length/radius/height of element [m]

The yield stress of SCC is in the range of 0–50 Pa, dependent on the mix design. Table 3 indicates the critical yield strength of concrete dependent on the height and

curvature (radius) of the panel. A reference with regard to the yield strength of concrete for 3DCP is a value of 3.0 kPa which is the initial static yield stress with a thixotropic build-up A_{thix} of 1.1 Pa/s and a short-term re-flocculation rate of 6.7 Pa/s [6]. Such thixotropic increase is much higher compared to what is typically observed in SCC, where an A_{thix} of 0.5 Pa/s already is considered a characteristic value of highly thixotropic SCC [7]. In another study, the yield strength of extrudable concrete was found to be in the range of 1.0–2.6 kPa [8], of which the upper boundary is much higher than the maximum values shown in Table 3.

Table 3. Critical yield strength $\tau_{0,\text{crit}}$ required for casting under a slope θ , depending on the mould radius R , the element length L and the element height h (for $\rho = 2\,400\text{ kg/m}^3$) [3].

Slope θ and $\tau_{0,\text{crit}}$		R = 1.5 m		R = 2.5 m		R = 5.0 m	
Horizontal length L	Element height h	θ	$\tau_{0,\text{crit}}$	θ	$\tau_{0,\text{crit}}$	θ	$\tau_{0,\text{crit}}$
[m]	[m]	[°]	[Pa]	[°]	[Pa]	[°]	[Pa]
0.80	0.025	15.5	157	9.2	94	4.6	47
0.80	0.050	15.5	314	9.2	188	4.6	94
0.80	0.100	15.5	628	9.2	377	4.6	188
2.00	0.025	41.8	392	23.6	235	11.5	118
2.00	0.050	41.8	785	23.6	471	11.5	235
2.00	0.100	41.8	1570	23.6	942	11.5	471

The structural build-up of the applied concretes was determined with the BML-viscometer and was in the range of 0.20–0.25 Pa/s [1, 3]. With an initial yield stress of 10 Pa and a thixotropic increase of 0.2 Pa/s the time can be calculated after which the critical yield stress determined with Eq. 1 is reached; this time is the minimum time at rest until the mould can be deformed. In Fig. 4, the time of deformation of the mould (X-axis) is compared to the theoretically derived time of deformation (Y-axis) with the 1:1 line being the minimum time before deformation.

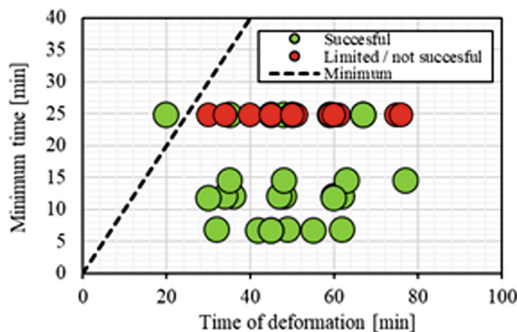


Fig. 4. Time of deformation of the mould compared to the time required to reach the theoretical yield stress indicated in Table 3 (initial yield strength: 10 Pa, $A_{\text{thix}} = 0.2\text{ Pa/s}$).

With the exception of a single point all dots are located at the right side of the minimum line. However, a number of experiments was not successful, as the red dots indicate and accordingly a second criterion is required for complete specification, which is discussed in the following section.

Critical Strain Capacity

Dependent on the interaction of the concrete with the mould, possible strain distributions are 1) at the left side of Fig. 5a) the neutral axis is at $h/2$ (flat sections remain flat after curvature, Bernoulli hypothesis) or 2) at the right side of Fig. 5a) the neutral axis is in the bottom of the mould, in which case $\epsilon_{\max} = h \cdot \kappa = h/R$. The second strain distribution corresponds with the idea of ‘wrapping’ the mould around a cylinder, since the mould surface itself is not stretched, but only curved, and a ‘no-slip’ situation is assumed. It was concluded that the second assumption of strain distribution fits best the boundary conditions [1]. In the transition period between fluid and solid states the allowable deformation angle $\theta_{\text{allowable}}$ is assumed to linearly increase over time due to the increasing yield strength of concrete, whereas the strain capacity of concrete decreases, e.g. as shown by the curved line, see Fig. 5b.

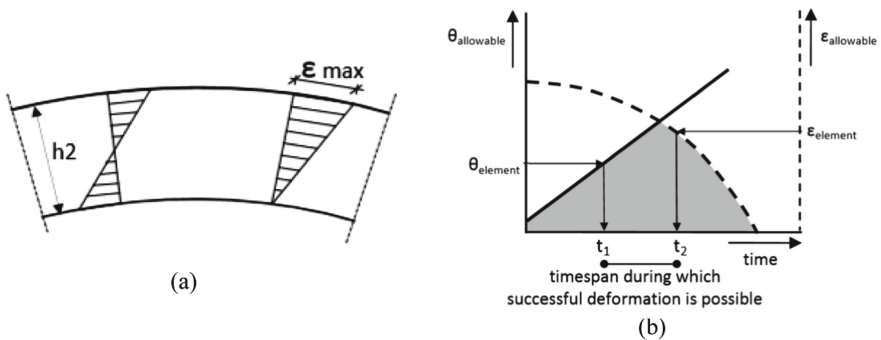


Fig. 5. Deformation of concrete a) two potential strain distributions over the element height of the cross-section and b) open window for the deformation of the mould (t_1 being the earliest moment and t_2 the latest moment before cracking occurs) [1].

Dependent on the geometrical boundary conditions, the ‘open time’ is the period within which the deformation capacity is sufficiently large and the concrete remains in the original shape of the mould after deformation (deformation and strain capacity decrease in time and the allowable slope goes up as the yield strength increases). The thickness and the curvature of an element determine the required strain capacity and not in all cases the two criteria with regard to yield strength and prevention of cracking can be balanced. The order of magnitude of strains in the research at Delft University of Technology was in the range from -75% (shortening) to $+35\%$ (elongation). Taking into consideration, though, that in the present research SCC with a very low yield strength was applied a relatively large strain capacity is expected. Evidence for larger strain capacities of flowable concrete was found by Troian [9], where elongation-strains of around $100000 \mu\epsilon$ were applied in the first hour after mixing without visible

cracking. Figure 6 compares the maximum strain (positive radius = positive strain of the concrete surface) of deformation experiments executed. With a maximum strain of about 17 promille all elements successfully were deformed, whereas with the largest strain of 33 promille the experiments in almost all cases were not successful. Obviously, below such material-related maximum (not depending on the yield strength), the open window mainly depends on the yield strength criterion and it increases the smaller the radius of the curved element is (or being negative). A study is ongoing with regard to the time-dependent changes during the deformation process.

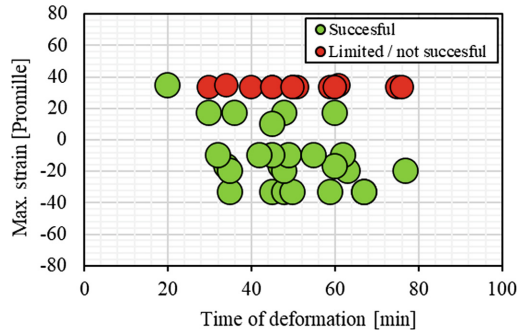


Fig. 6. Influence of time on the maximum strain capacity of self-compacting concrete.

3 Transition from the Fresh to Hardening State

3.1 Mechanisms Acting During the Transition

With the advance of the 3DCP technology, important knowledge was gained with regard to the mixture optimization, fresh and hardened state properties, test methods and prediction of structural performance, a development which is still in progress. Such knowledge was limited before to only a few areas, e.g. pumping, rheology of flowable concretes, utilisation of green strength for concrete production or the prevention of bleeding and segregation. This knowledge can be further exploited to improve other (new or existing) production processes. 3DCP poses two main requirements with regard to the concrete 1) printability and 2) buildability. Only within a short period of time (open window) optimized processing can take place [10]. Buckling as well as the surpassing of the material strength (or a combination of the two) are potential reasons for failure after material deposition. Flocculation and structuration processes are ongoing and contribute to the build-up of structure over time [11]. Different properties in time and under different shearing conditions have the following important reasons:

- Structural build-up due to thixotropy caused by colloidal attractive forces;
- Progress of degree of hydration with contact points between binding grains;
- Chemical acceleration of binding rate;
- The addition of components with faster growing reaction products;
- (Micro)fibrils can be added to increase the yield strength.

The chemistry of cementitious materials can be significantly altered by the addition of admixtures. For production, temperature effects also have to be taken into account, in order to have sufficient time to place the material. During the production of test elements with the FMP the deformation of the mould frequently was executed after about 45 min; this period can be essentially shortened with acceleration of hydration (essentially also shortening the effective time of the superplasticizer) or by design of a more thixotropic concrete. For 3DCP the acceleration of the increase of stiffness and strength is subject of many research projects. In [11] accelerators are reviewed: the desorption of retarders, the use of C-S-H seeds, soluble inorganic salts or organic compounds are effective measures for mix design. In particular, silicate and aluminium salts are admixtures that can produce a very quick setting. The use of alternative binders (e.g. alkali-activated binding, rapid setting calcium-aluminate or calcium sulfoaluminate cements) also yield a faster strength increase. Beside rapid-hardening mix designs, execution measures can be supportive in optimizing the production conditions (e.g. heat curing or microwave acceleration).

3.2 Development of Strength and Reduction in Strain Capacity Transition

The flowability of printed concrete is not comparable with flowable concretes, as their first task is to remain in the position where they were placed. The initial part of deformation of a Bingham material (before flow is initiated) is therefore more relevant for the extrusion process of 3DCP. For the filling of the flexible mould first the critical strain has to be surpassed and flow initiated. Over time, the yield strength increases and the strain capacity decreases, both parameters are essential to consider for the deformation of the mould. Locations with up-bending of the mould are characterized by important strains in the concrete, whereas at down-bend locations, the tensile stress is carried by the formwork. Strain can be distributed over a wider area, or it locates at the position with the largest strain.

An important difference between 3DCP and the FMP is the period after mixing, during which the transition from a flow behaviour or visco-elastic behaviour towards elastic deformation takes place. After mixing, concrete in 3DCP often does not exceed the range of critical strain to reach the material yield strength (flow), with the exception of the slipping layer in contact with the pumping pipe, whereas this is very important for the production with the FMP during the filling phase. Furthermore, the waiting time before deforming the mould compared to the time required to obtain sufficient buildability for 3DCP is significantly longer for the initially flowable concrete used for the FMP. The difference can be a factor of 5 or more in time, which makes the flexible mould process more robust. Not only is the transition time later after mixing, but also the period of transition (open window) can be longer (dependent on the geometry of the panel to be produced). Tests can be executed during the initial phase to determine the yield strength e.g. with the slump or slump flow test, while the concrete remains in horizontal position, to determine the appropriate moment of deformation. Figure 7 shows a typical result of a vane test executed with a material having a yield stress [10], where the material exhibits a more or less elastic behavior until the shear stress is reached, beyond which flow is initiated.

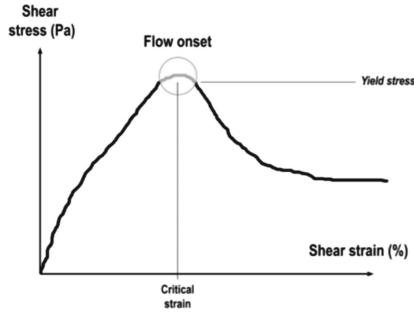


Fig. 7. Shear stress as a function of shear strain [10].

Similar curves can be obtained from triaxial compression testing [12], with which the transition in the plastic stage of relatively stiffer materials can be assessed. Yield stress, modulus of elasticity and critical strain are time-dependent and over time the hydration process has a larger contribution compared to the structural build-up [13]. Instead of Bingham flow behavior determined with a rheometer, which is more applicable for flowable materials, the material characterization of collapse was assessed with the Mohr-Coulomb criterion applied on compression/shear test results [14]. However, the initial critical strain is relevant for both vane and triaxial compression tests and it indicates the deformability until the maximal stress is reached at a specific moment of time. The higher the yield stress, the smaller the strain capacity becomes [14]. An initial stiffness is required for 3DCP to limit the deformation after the extrusion, which is therefor a lower bound. In contrast, the FMP has an upper bound with regard to stiffness in order to be able to follow the deformation without the localization of cracks. After the deformation of the mould the concrete itself has to stay in shape. In [10], the stiffness parameter E is defined, which has to be exceeded during 3DCP in order to obtain a stable structure dependent of the boundary conditions of the structure. The critical strain related to the peak shear stress/yield stress is of the order of a few % and about 2% [4]. This value is comparable with the results on the maximum strain capacity shown by Fig. 6. The maximum strain capacity is for the FMP an upper bound and a complementing criterion with the yield strength.

4 Conclusions

This paper discusses the flexible mould process and compares it with regard to production boundary conditions with 3D concrete printing. Based on the discussion the following conclusions can be drawn:

- Both production processes are examples of optimized combinations of material design, execution method and structural performance.
- 3DCP and the flexible mould process are production processes with significant differences. However, the discussion of the time-dependent transition and

magnitude of and strain at shear stress indicates similarities with regard to basic production requirements.

- The reliable measurement of material properties for both processes is challenging, due to the quick change of the material properties during the first hour and the time and handling required for various measurements.

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Physico-Chemical Characterization at Early-Age of 3D Printed Mortar

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Abstract. The rheology is the key factor that controls the 3D printability of cement-based materials. Indeed, the printed material should satisfy both good workability retention to ensure successful extrusion and a well-adapted green strength to support subsequent layers without collapsing. This requires a tricky control of the physico-chemical structuration kinetics. In the present study, in addition to dynamic rheology, ultrasonic wave propagation test was used to monitor the evolution of the elastic and shear moduli with time. Furthermore, isothermal calorimetry measurements were carried out to quantify the chemical evolutions underlying the early-age behavior of 3D printable cement-based material. A comparative analysis was conducted to correlate rheological measurements with those obtained using non-destructive and calorimetry test methods. Based on the obtained results, a new testing methodology combining the rheological and mechanical properties, as well as isothermal calorimetry measurements is proposed. The proposed method allows a better understanding of the physico-chemical structuration kinetics during the setting process, hence allowing proper optimization of the mixture design from rheological and mechanical points of view.

Keywords: 3D printing · Cement-based material · Rheology · Elastic properties · Thixotropy · Green strength · Non-destructive test methods · Structuration kinetics

1 Introduction

The author's ongoing research is mainly focused on 3D printing as an innovative construction technic to achieve distinctive advantages over conventional construction methods. Higher construction efficiency, less intensive labor and waste production, as well as the improvement of architectural freedom to produce geometrically complex elements are the major benefits that can be achieved [1]. The properties at fresh state of 3D printed cement-based materials are crucial for successful printing process. The mixture design of cement-based materials needs, therefore, significant improvements to meet the requirements of 3D printing. Indeed, several rheological requirements, especially structuration kinetics, should be considered to tailor a 3D printable mix design. The required properties involve adequate fluidity to facilitate the extrusion and sufficient

rigidity to ensure good shape stability. In fact, the printed layer should withstand its own weight and sustain the induced stresses resulting from the successive layers. Thus the printing material must gain an early green strength compatible with the printing speed [2]. Therefore, a proper control of the early-age properties of materials is significantly important, especially its kinetics of structuration. The development of rheological and mechanical properties at early age is associated with two different mechanisms, one reversible (referred to thixotropy) and another irreversible. A deep understanding of the material's behavior and its time-dependent variation in 3D printing process is required to optimize the targeted properties, while considering the printing requirements, including pumpability, extrudability, and buildability [3]. Efficient, reliable, and non-destructive test methods with good repeatability should be used to allow adequate capturing of the structuration, while considering the contribution of thixotropy.

A reliable method combining both rheological and ultrasonic waves measurements is conducted in the present study. The proposed method is then successfully used to evaluate the physical and chemical structuration of cement-based mixture at rest. Dynamic rheometry was used to monitor the evolution of structural build-up of the mixture, while the ultrasonic waves were employed to follow the development of mechanical properties. A comparison between the evolution of structural build-up and both the elastic and shear moduli was quantified and discussed. A special interest was given to the kinetics of structuration during the first few hours after mixing, corresponding to the induction period. Moreover, isothermal calorimetry measurements were carried in order to quantify the role of chemical reactions on the evolution of structuration of 3D printed cement-based materials.

2 Materials and Test Methods

2.1 Materials

The investigated 3D printable mortar mixture was proportioned using portland cement type CEM I 52.5 N, fly ash (FA), silica fume (SF), and very fine sand. A compatible Polycarboxylate superplasticizer (SP) was added to increase flowability of the investigated mixture. The particle-size distributions of the materials are shown in Fig. 1. On the other hand, the mixture proportions of the investigated mixture are summarized in Table 1.

2.2 Mixing Procedure

All the mortar samples were prepared according to the same mixing procedure to eliminate the effect of shear history. First, dry cement, fly ash, and silica fume were mixed for 60 s at a slow rotational speed using a planetary mortar mixer. Then, 2/3 of mixing water was added and the mixture was mixed for 60 s. The remaining water along with the superplasticizer were then added, and the mixture received another 60 s of mixing, before introducing the sand to the mixer. Afterwards, the mixture received another mixing of 1 min. Finally, the edges of the bowl were scraped, and the speed of mixing was increased for an additional mixing of 2 min to ensure a homogeneous mixture.

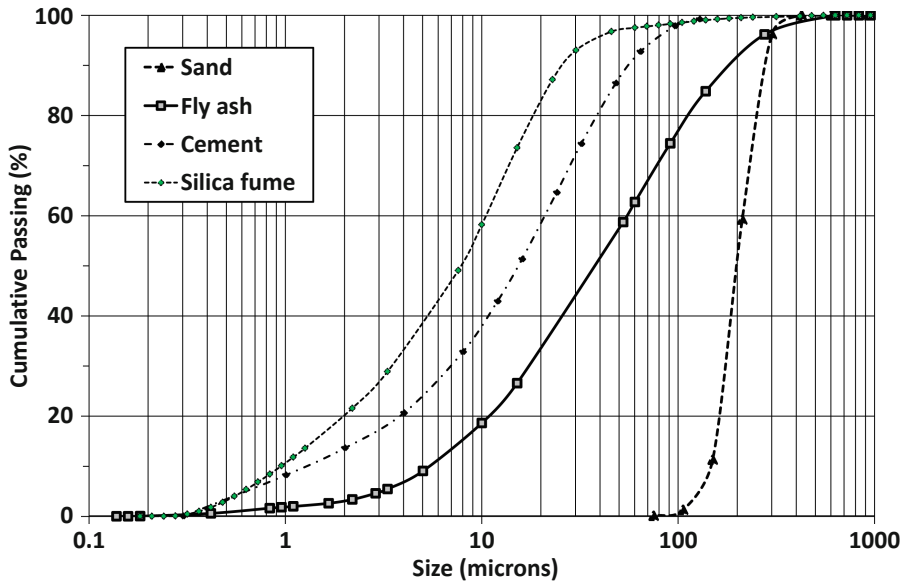


Fig. 1. Particle-size distribution of the powders and sand

Table 1. Mixture proportions of the investigated 3D printable mortar

Sand (kg/m ³)	CEM 1 (kg/m ³)	FA (kg/m ³)	SF (kg/m ³)	Water (kg/m ³)	SP (% woc)
981	649	185	93	260	1.2

2.3 Test Procedures

It is worthy to mention that all the performed tests were carried out in parallel using the same batch of mortar.

Isothermal Calorimetry

An isothermal calorimeter TAM air was used to measure the heat flow of mortar samples. This can allow better understanding of the influence of chemical evolution on the properties at early age of 3D printable mixture. The measurements were performed on mortar samples of 100 g at a controlled temperature of 20 °C. The principle of the calorimetric measurements is detailed in [4]. This test was carried immediately after mixing at a well-defined time corresponding to the spread flow tests. This can guarantee an adequate calculation of both heat rate and cumulative heat, expressed in W/g and J/g, respectively. Due to both instrumental and operating limitations, calorimetric

data cannot be considered as reliable for the first 45 min of the experiments [5]. This time is necessary for the sample to reach its equilibrium temperature.

Rheological Measurements

All rheological measurements were performed at a constant temperature of 20 °C using the Discovery Hybrid Rheometer from TA instruments. The rheometer is equipped with vane geometry. The diameters of the cup and bob are 30.36 mm and 26.198 mm, respectively, providing a shear gap size of 4 mm. On the other hand, the amplitude sweep tests were carried out to determine the critical strain of the investigated mixture, hence allowing investigating the rheological properties of the 3D printable mixture at rest (i.e. within the viscoelastic linear domain). The measured critical strain ranged between 10^{-5} and 10^{-4} . Small amplitude oscillatory shear (SAOS) tests were then carried out at shear strain of 10^{-5} , which is lower than the critical strain to ensure a nondestructive test of the tested material [6], and an angular frequency of 10 rad/s. The measuring system and tested samples were covered with a lid to prevent water evaporation during measurements. During the test, the mortar samples were first pre-sheared at a constant shear rate of 200 s^{-1} for 2 min, and then followed by a large amplitude oscillatory shear (LAOS) at a shear strain of 5% and an angular frequency of 100 rad/s for 10 s. This preconditioning was shown to provide a good dispersing performance [7]. Each test was performed three times to evaluate the repeatability of the measurements.

Ultrasonic Measurements

The evolution of elastic properties at early age of mortar mixtures was monitored using the FreshCon system. The test procedure is described in [8]. The evolution of elastic (E_{dyn}) and shear moduli (G_{dyn}) was determined from the velocities of compression and shear waves, according to equations given in [9]. The test was performed in controlled room temperature of 20 °C.

3 Results and Discussion

The determination of physico-chemical structuration kinetics and setting time is necessary to develop deep understanding of green-strength evolution. This can therefore contribute in optimizing 3D printable cement-based materials with adapted green-strength kinetics, as defined in [10]. The experimental results of this study allow investigating the interaction between the hydration evolution and physical structuration of 3D printable mixture.

- The first region is characterized by an early evolution of elastic properties, just before the acceleration of hydration reactions. This is referred to a period corresponding to an open time. This time is critical for the printing process as all the properties should be optimized to achieve the printing requirements [11]. During the first hours following the end of mixing sequence, the particles can flocculate due to van der Waals attraction forces. As a result, an interacting network of particles and

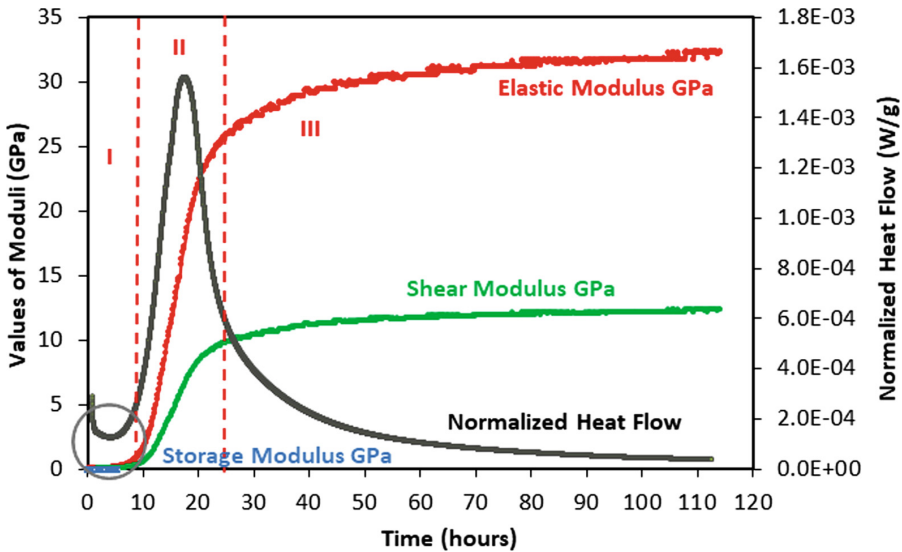


Fig. 2. Evolution of elastic, shear, and storage moduli as well as normalized heat flow with time. The zoomed part is shown in Fig. 3.

flocs is formed, which lead to a linear increase of the storage modulus G' , as shown in Fig. 3 (*Phase A*). It was reported in the literature that during the dormant period, the volume of formed hydrates increases linearly with time, hence resulting in a linear increase of G' [12]. This evolution is accompanied by an increase in the number of pseudo-points contact between the flocculated particles at rest, which result in higher structuration rate of the material. This leads to the formation of successive interconnected percolation paths, which correspond to the transitional phase (*Phase B*) until reaching a steady state (*Phase C*) [13]. The evolution of storage modulus G' was conducted during the dormant period. As a consequence, the growth of G' presented in Fig. 3 originates mainly from physical mechanisms. In order to evaluate the effect of hydration on the structuration rate, the results obtained using the FreshCon test set-up were used.

- Immediately after the dormant period, a percolation threshold has been reached and continuous paths of hydrates can actually be observed in the microstructure of cement paste [14]. Hence, the hydration rate accelerates, and a non-linear structuration is observed after 8 h of age, as shown in Fig. 2. The degree of hydration of 0.03 corresponds approximately to a period of 8 h of age (Fig. 4). This is followed by a rapid structuration occurring at the same time as the acceleration of hydration. It is worthy to mention that the time at which this increase takes place correspond to the initial setting period [15]. The first significant increase of the elastic modulus can also be observed, then the gain in compressive strength occurred, while the stiffness development evolves faster than the strength growth [16].
- The third region starts immediately after the occurrence of structuration has taken place. In this region, a less inclination compared to that of the second phase was

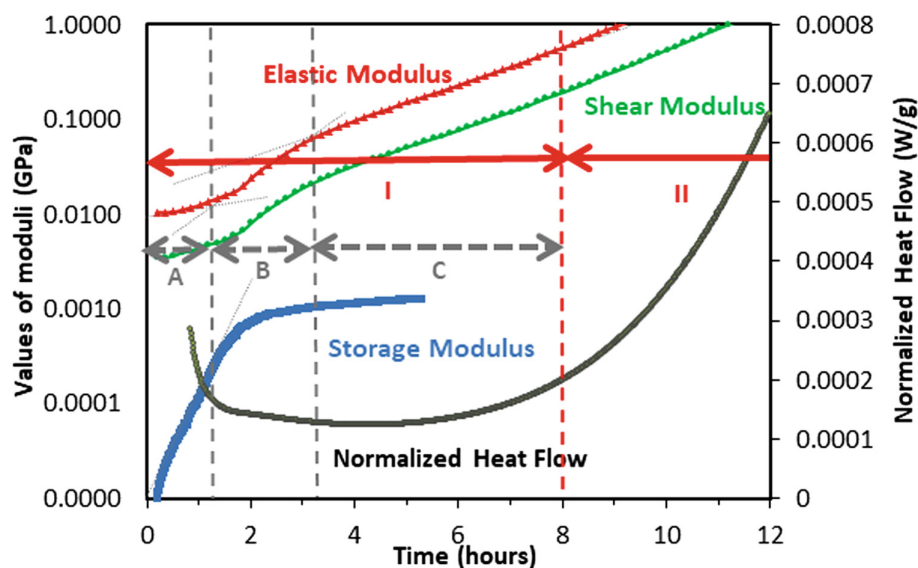


Fig. 3. Evolution of elastic and storage moduli, as well as the normalized heat flow

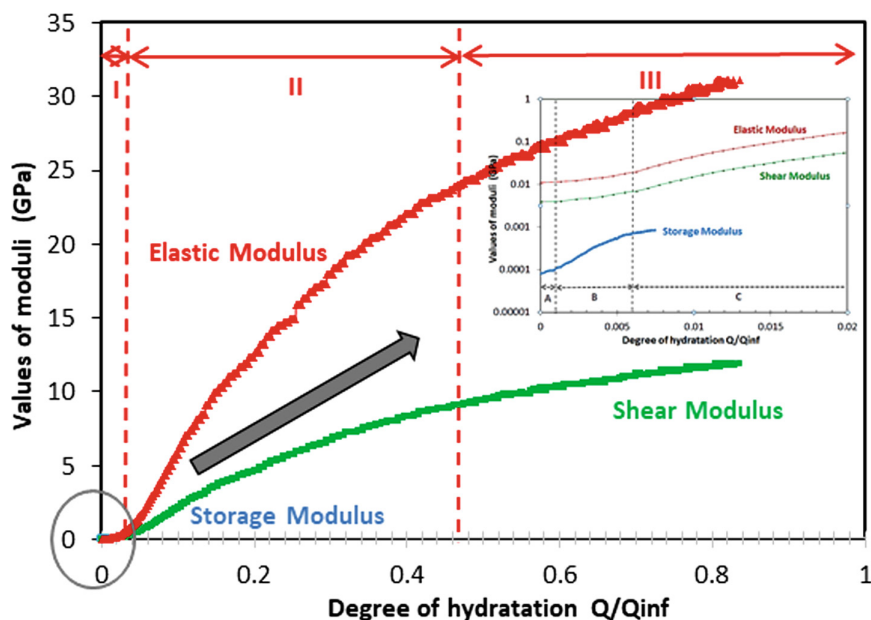


Fig. 4. Evolution of elastic and shear moduli with hydration kinetics

observed. The degree of hydration of approximately 0.5 corresponds to the end of setting. These results are in good agreement with those reported in literatures [10, 17].

It is important to mention that the increase in storage modulus follows the same trend observed with the elastic and shear moduli. Therefore, the ultrasonic waves test is shown to be efficient test method to monitor the evolution of structural build-up, especially after the initial setting time, when the rheometric measurements cannot be carried out for practical considerations.

4 Conclusions

The main objective of this investigation is to develop new testing methods that can be used to efficiently monitor the evolution of structural build-up of cement-based materials. The proposed approach consists in combining the rheometric and ultrasonic measurements. The obtained results of this investigation show that these two complementary tests are shown to be efficient in describing the structuration kinetics of 3D printed mortar. Indeed, taking into account the fact that rheological measurements can be evaluated before the initial setting, during which compressional and shear waves are difficult to intercept, combining the two tests gives an overall view of the evolution of the material properties, hence allowing reliable measurements of its structuration. Moreover, the evolutions of storage modulus (G') and both the elastic and shear moduli with time show similar pattern. The proposed method allows a better understanding of the physico-chemical structuration during the setting process from the rheological and mechanical points of view. This method will be further investigated by printing small- and medium- scale elements to evaluate its capability in reflecting the evolution of rheological properties during the printing processes.

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Gravity Driven Tests to Assess Mechanical Properties of Printable Cement-Based Materials at Fresh State

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Abstract. The prediction of the stability of fresh cementitious materials during 3D printing is required in order to find adequate process parameters such as building rate or time gap between layers. Schematically, the process efficiency depends on a balance between the rate of strengthening of the material and the building rate that increases the self-weight that the freshly printed structure must withstand. The first deposited layer of fresh cementitious material must be stiff enough to avoid squeezing effect, and the material has to be rigid enough for the in-print structure not to buckle. This is even more crucial for slender cantilevered structures. Also, cracks may appear in sharp angles of the printed shapes. To predict and avoid those printing defects, the determination of various rheological (shear, compression and tensile yield stresses) and fresh-state parameters of the material (elastic modulus) are required. As rheometer and ultrasonic measurement devices are not usually available on the production site, there is need to develop simple and accurate tests that can provide mechanical parameters for the prediction/verification of the stability of the structure during printing. For instance, instantaneous and continuous penetration tests can be used to evaluate the material yield stress and its evolution over time.

In this work, a special attention will be paid to simple tests such as the bending of a circular cross-section beam of fresh cementitious materials and/or the self-tension tests of cylindrical cross-section laces. The first one can be used to compute the apparent elastic modulus, while the second provides the tensile yield stress. Measured parameters are then compared with the ones computed from dimensional compression test and shear vane tests in order to validate the obtained results.

Keywords: Elastic modulus · Yield stress · Self-tension test · 3D printing · Cantilever beam

1 Introduction

Concrete digital manufacturing is nowadays a major challenge for research within civil engineering field [1–3]. A lot of new building projects deal with complex and

hard-to-reach shapes such as artificial reefs, architected columns and structures with multi-functionalities. Digitally controlled printing process of concrete may reduce economic and environmental side effects (mostly by saving materials using topology optimization) and improve working conditions and safety at the same time.

Various techniques of 3D printing currently exist but extrusion/deposition method is probably the most studied and explored. This method requires a perfect control of the material behavior before, during, and after the printing. Many studies have highlighted some rheological requirements [4] which can be described as a competition between strengthening and rigidification rate of the cementitious material and the printing rate that increased both the weight of the structure (compressive failure of the base layer) [5] and the elastic deformation (that tends to induce compressive buckling under its own weight) [6]. The problem of elastic strain is more pronounced with cantilevered and slendered structures. The unexpected elastic deformation of a cantilevered single layer can dramatically increase the risk of buckling and may lead to a local or global instability of the structure. Therefore, the description of the material elastic behavior is required to keep the printing process under control.

Concrete must also be fluid enough to be pumped, and ductile enough to avoid micro-cracks and damages in sharp turning point of structures. The process is also influenced by the nozzle design. Nozzle design divides the deposit step using three different techniques: layer pressing method, gravity driven deposition and extrusion of an “infinite brick” [7]. The choice of one of these three deposit methods induces consequences on both rheological requirements of materials and robotic complexity of the printing. For example, during free-gravity-driven deposition, the material is bent under its own weight and can be slightly stretched or squeezed, depending on the ratio between the nozzle velocity and the material flow rate. This may lead to formation of cracks and elastic strain which must be under control for a successful printing.

Characterizing tensile behavior of fresh material is an important aspect that should be taken into account to ensure smooth surface finish of the fresh cementitious material layers and avoid micro-cracks that may lead to durability issues [8].

It is even more crucial when dealing with underwater 3D printing process of concrete where the material has to resist water washout: porosities and micro-cracks must be as small as possible [9]. In this paper, two gravity driven tests are used in order to evaluate the tensile strengths and the apparent elastic moduli of fresh cementitious materials using vertical ram extruder and horizontal screw extruder respectively. Tests are performed on firm mortars, with and without cellulose ethers, and results appear to be very consistent with rheological measurements.

2 Materials, Methods and Basic Measurements

2.1 Concrete Formulation

Tested materials are two mortars made from standard sand EN 196-1 (55% weight of dry material), cement CEM I 52.5 (34% weight of dry material), and limestone filler (11% weight of dry material). The tested formulations have effective water to cement ratio equal to 0.37 and 0.39, and contain a high range water reducing admixture HRWRA. The HRWRA to cement mass ratio is 0.15%. Both mortars were tested with and without cellulose ethers CE (Walocel MKX 15000 PF01 provided by DOW Chemical Company).

Such viscosity modifying admixture modifies the workability of the cementitious material [10]. In order to take into account this influence, the water content of the mortar containing CE has been adjusted in order to maintain the same elastic modulus as the one of the reference mix without CE. All values are summarized in Table 1.

Table 1. Mix design and updated W/C ratio values

Mix design	Target W_{eff}/C ratio	Cellulosic ether to water ratio	Adjusted W/C ratio
1	0.37	0.0%	0.37
2	0.37	1.25%	0.40
3	0.39	0.0%	0.39
4	0.39	1.25%	0.42

2.2 Compressive Strength Measurements for Apparent Elastic Modulus Determination

Behavior of cement-based materials is often described as an elastic solid, as long as the yield stress is not exceeded. Material behavior was studied using one dimension compression test between two lubricated plates [9]. A mean value of pseudo-elastic modulus can be computed for each mix design from the slope of the force vs displacement curves. Samples of 50 mm diameter with a slenderness equal to one, were tested with a displacement rate of 0.5 mm.s^{-1} . Compressive yield stress can also be obtained and results can be summarized in Table 2. As stated before, the mix design of material was made in order to obtain nearly the same pseudo-elastic modulus.

2.3 Static Shear Yield Stress Measurements

The measurement of the static shear yield stress is basically the most widely used technique to estimate the instantaneous strength of the material and compute the structural build-up rate [11]. It is mostly performed using stress growth test at low constant shear rate. During 3D printing, this yield stress value governs

the extrusion force and is involved in the overall stability of the structure. In this study, the shear static yield stress is measured using a vane geometry of 22 mm diameter and 40 mm high. A rotational shear rate of 0.1 s^{-1} is imposed for 80 s. Results are summarized in Table 2.

Table 2. Shear yield stress and pseudo-elastic modulus

		τ [kPa]	Std. deviation $_{\tau}$ [Pa]	E [kPa]	Std. deviation $_E$ [kPa]	$\sigma_{y,comp}$ [kPa]
$W_{eff}/C = 0.37$	Without CE	2.6	57	116	12	74.46
	With CE	1.4	44	105		30.48
$W_{eff}/C = 0.39$	Without CE	3.7	62	39	6	42.66
	With CE	3.5	40	38.5		24.48

The two mix designs exhibit quite different pseudo-elastic moduli. Here, the compressive behavior seems to be driven by contacts between sand particles for the lower water to cement content ratio, while it seems rather controlled by cementitious matrix behavior when the water content increases. Actually, this contribution of cement paste on the global mix behavior also strongly depends on the sample slenderness. This has to be regarded as specific to the studied cases, with the given aspect ratio.

2.4 Developed Gravity-Driven Tests

Cantilevered Mortar Beam. The principle of the test is based on the measurement of the elastic deformation of a cantilevered mortar beam. It consists in capturing the deflection of a circular cross section of mortar extrudates exiting from a screw extruder nozzle. Under its own weight, the cantilevered beam bends and the tip deflection increases with the free length. Before collapse and plastic flow, the mortar extrudate exhibits an apparent elastic behavior and the apparent elastic modulus can be determined. Moreover, the length for which the extrudate does not display an elastic-like behavior can be associated with a plastic yield stress that can be compared with tensile and shear yield stress measurements.

In this study, two extrudate diameters (15 mm and 35.5 mm) and different extrusion velocities ranging from 2 mm/s to 14 mm/s are tested in order to evaluate the viscous effects on the measurements. From video recording, (see Fig. 1), beam deflection can be estimated using Pymecavideo software¹ and compared with an analytical solution.

This circular fresh concrete cross section is subjected to the effect of transverse shear strain: Timoshenko beam theory [12] will be used to account for these

¹ Pymecavideo software was used to capture every 5 to 25 ms the beam length evolution and associate deflection. Scale is define before plotting each test.

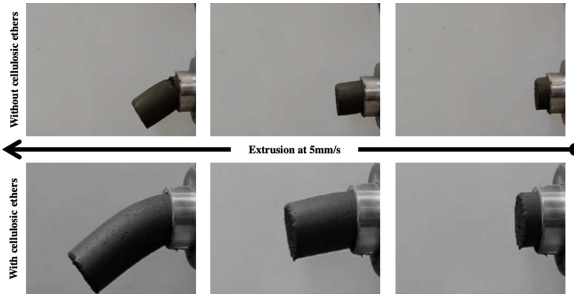


Fig. 1. Cantilevered beam extrusion test using mortar at $W_{eff}/C = 0.37$

effects. According to St Venant principle, σ_{xx} and τ_{xz} respectively depends solely on M_y and V_z : bending and shear contribution could be dissociated in order to describe the bending deformation. The current study deals with a circular cross section: values of the second moment of area $I_y = \frac{\pi \cdot D^4}{64}$ and the reduced cross-section for the calculation of deformation under shear stress $S_r = \frac{9}{10} \cdot S$ can also be used.

Using material parameters as input characteristics describing our load case, final bending strain d can be defined.

$$d = \frac{512 \cdot \rho \cdot g \cdot \delta L^4}{E \cdot D^2} + \frac{5 \cdot \rho \cdot g \cdot \delta L^2}{9 \cdot G} \quad (1)$$

Considering the evolution of bending deformation with free length, it is interesting to compare analytical results with cantilevered beam deflection test in order to test the reliability of the model (based on elastic modulus measured using one dimensional compression test and assuming that the poisson ratio is 0.4). Also, it is possible to estimate an apparent elastic modulus. Estimated values are summarized in Table 2.

Self-tension Test. The self-tension proposed in this study consists in measurement of the self-tension strength of extrudates leaving a vertical extruder at constant velocity. Once the load produced by the material own weight induces the tensile strength of the material, the extudate breaks at the extruder exit. The aim is to perform this test in quasi-static conditions: test will be carried out for relatively low flow rates of 25 mm/min and 50 mm/min (Fig. 2).

Device consists of a 5 cm diameter and 20 cm long cylindrical extruder fitted with a piston, placed on a 45 cm high steel frame. Once the extruder is carefully filled to avoid bubbles and the piston is put on the top of material, the device is placed in a compressive machine equipped with a 10 kN load cell. Piston displacement is controlled by displacement transducer and the instantaneous applied force is recorded. Two diameters of 14 and 18 mm are used to study the dependency of the results on geometrical effects. Extrusion rate of concrete

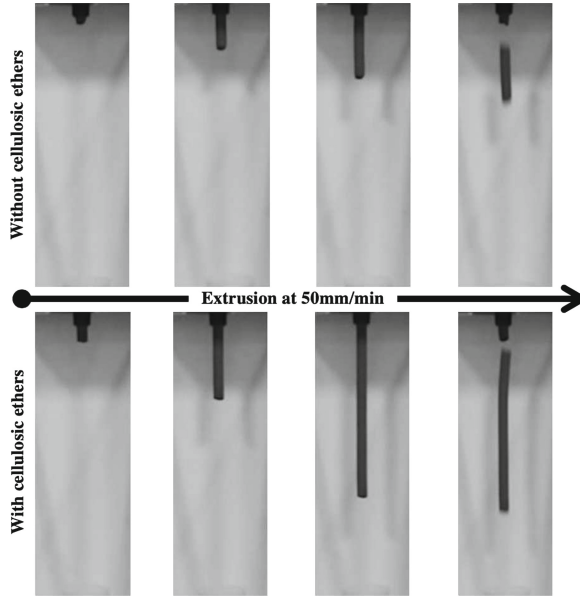


Fig. 2. Gravity tensile test using mortar at $W_{eff}/C = 0.37$ using 14 mm profile

sample V_{sample} at steady state regime can be checked by taking into account the section reduction ratio and imposed piston velocity V_{piston} as follows in Eq. 2.

$$V_{sample} = V_{piston} \cdot \frac{D_{piston}^2}{D_{die}^2} \quad (2)$$

This experimental test proposes to assess tensile strength using two different ways:

- A computed tracking of a concrete sample during extrusion using an image analysis software with, at least, 3 repetitions of measurement: $m_{sample} = \frac{L_w}{\pi R^2}$
- A method which consists in weighing pieces of broken samples.

Ultimate strength can be obtained by taking account of some density deviation in Eq. 3.

$$\sigma_u = \frac{m \cdot g}{\rho \pi R^2} = \rho g L_{extruda} \quad (3)$$

3 Results

3.1 Bending Behavior

Characterization of Pseudo-Elastic Domain. Values of apparent elastic-modulus are computed applying Timoshenko theory (Eq. 1) to the linear plotted

part (Fig. 3) of the recorded deflection curves (before the deflection sudden drop). Based on these results, summarized in Table 3, it is interesting to note that the elastic domain increases with the CE dosage and provides ductility to the material.

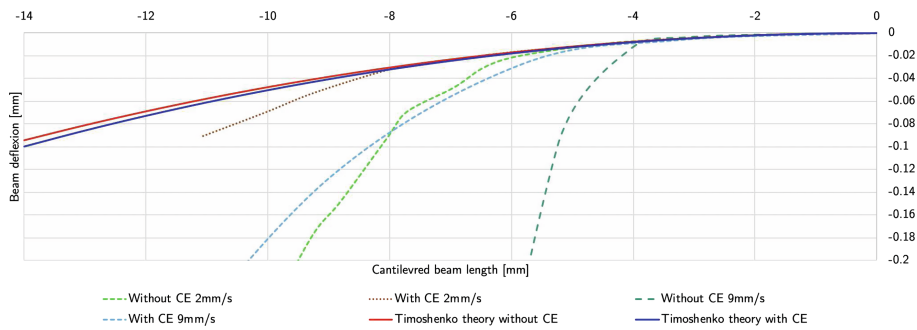


Fig. 3. Analyse of the elastic domain in bending, $W_{eff}/C = 0.37$

Table 3. Fitted values of pseudo-elastic moduli in assumed elastic domain

		Cantilever length at the end of domain [mm]	E value used with Timoshenko theory [kPa]	Optimized elastic modulus E_{opt} [kPa]
Without CE	2 mm/s	5.2	116	111.67
	9 mm/s	3.8	116	126.11
With CE	2 mm/s	7.9	105	107.24
	9 mm/s	4.5	105	103.65

Measured Properties. Cantilevered beam tests provide elastic behavior but determination of viscoplastic properties could extend the tests' relevance. Tests have shown that extrusion rate has an effect on the behavior once the plastic regime is reached. It suggests that viscous aspect should be taken into consideration as shown in Fig. 4.

Even if viscosity seems to have a significant effect on the sample strain, bending behavior is more influenced by the material plastic flow. Further works will deal with the ability of such tests to study plastic strength of the material (combining bending and shearing loading) using this kind of gravity driven test. The aim is to identify the stress at the beginning of plastic domain.

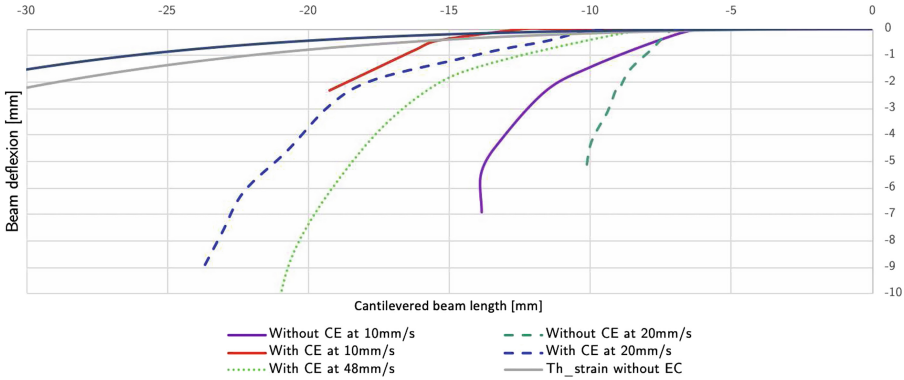


Fig. 4. Bending deformation of cantilevered beam $W_{eff}/C = 0.39$

Table 4. Comparison between measured compressive and tensile yield stress

		$\sigma_{y,comp.}$	$\sigma_{y,tens.}$	Deviation	
		[kPa]	[kPa]	[kPa]	[%]
$W_{eff}/C = 0.37$	Without CE	74.46	2.42	72.04	$\approx 3000\%$
	With CE	30.48	5.16	25.32	$\approx 590\%$
$W_{eff}/C = 0.39$	Without CE	42.66	1.64	41.02	$\approx 2600\%$
	With CE	24.48	6.06	15.42	$\approx 350\%$

3.2 Tensile Behavior

Self-tension test consists in measuring the length of an extruda leaving vertical extruder before it breaks under its own weight: the length of the sample at steady state regime is the same than the length of the calculated sample using Eq. 2. Ultimate strength of fresh mixes could be obtained by analyzing discontinuity of the curve. Estimation and dispersion of breaking strength results for each size of extrusion profile are given in Table 5.

Results attest that the flow in the tank is pretty much the same than the flow at the extruder die as shown in Fig. 5. Asymmetric behavior between compressive and tensile yield stress, compiled in Table 4, qualitatively informs us that plasticity criterion, such as Von Mises criterion, is not really accurate to describe complex phenomena observed in fresh cement base materials.

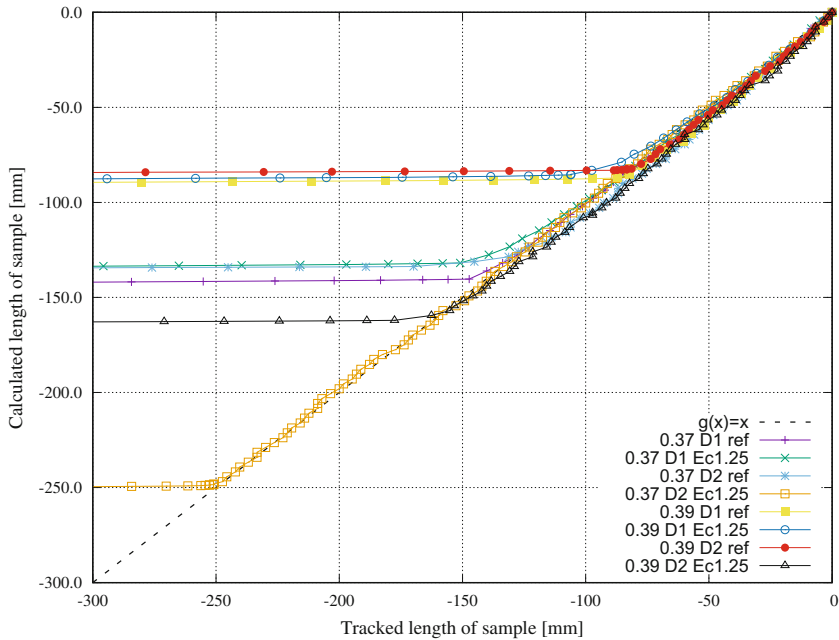


Fig. 5. Comparison between calculated length of sample considering flow into the piston, and plotted position of sample during extrusion process - $V_{piston} = 50 \text{ mm} \cdot \text{min}^{-1}$

Table 5. Tensile strengths for 14 mm extrusion profile

		ρ	$m_{weighing}$	L_{sample}	m_{calc}	$Std.deviation_w$	σ_{tens}
		[g/L]	[g]	[mm]	[g]	[g]	[kPa]
$W_{eff}/C \cdot \Phi_{14mm}$	0.37	25mm/min Without CE	2250	29.53	81.00	28.06	3.41
		25mm/min With CE	2071	61.74	193.00	61.52	0.51
	50mm/min	Without CE	2243	44.10	142.00	49.02	6.01
		With CE	2113	41.22	132.00	42.94	1.99
	0.39	25mm/min Without CE	2246	17.92	53.00	18.32	3.96
		25mm/min With CE	2090	53.20	167.00	53.73	0.81
$W_{eff}/C \cdot \Phi_{18mm}$	0.37	50mm/min Without CE	2229	31.49	89.00	30.54	5.31
		50mm/min With CE	2095	29.00	88.00	28.38	1.80
	0.39	25mm/min Without CE	2227	48.26	82.00	46.46	3.39
		25mm/min With CE	2067	98.86	185.00	97.33	1.03
	0.37	50mm/min Without CE	2236	71.04	134.00	76.25	6.08
		50mm/min With CE	2048	128.27	249.00	129.75	1.82
	0.39	25mm/min Without CE	2224	34.12	57.00	32.25	3.26
		25mm/min With CE	2080	130.38	251.00	132.85	1.47
	0.39	50mm/min Without CE	2243	50.86	84.00	47.95	5.87
		50mm/min With CE	2051	84.16	163.00	85.08	1.26

4 Conclusion

Two new tests called ‘cantilever test’ and ‘gravity driven tensile test’ are proposed in this study to characterize cement based pseudo-elastic behavior during printed layer deposition. These techniques, based on image analysis, allow to estimate some domains of deformation and then estimate a characteristic value of critical stress. It has also highlighted that some dynamic aspects are at the origin of additional strains: a link between material extrusion rate (directly related to shear rate) and material behavior during printing process is important.

From a purely mechanical point of view, this study highlights an important asymmetry between yield stress under tensile and compressive loads. This deviation of measured values has to be considered to describe plasticity domain of material: VonMises criterion often used to describe plasticity needs, should be coupled with other parameters to be used with alternative cementitious mix designs.

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Characterizing Extrudability for 3D Concrete Printing Using Discrete Element Simulations

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Abstract. 3D Concrete Printing (3DCP) is a novel automation construction technique, which interested many researchers extensively in the past few years. Among the major research interests in the specific area, the rheology of 3DCP material attracted more researchers recently. Due to the significantly different rheological requirements in extrusion and layer-wise construction stages, proper understanding and characterization of the rheology of 3D printable concrete are required. Extrudability criteria of the material highly depend on the extrusion geometry, extrusion parameters, and the flow type occurring while extruding (i.e. plug flow or highly sheared flow). Hence, numerical simulation tools may be important to understand the flow behavior and extrudability criteria of 3DCP. Therefore, in the current study, the Discrete Element Method (DEM) was used to model the flow behaviour of 3D printing concrete and to characterize the extrudability. A user-defined two-phase hardcore-softshell contact model was developed for particle interactions and the model was calibrated using the experimental orifice extrusion test results. The developed model was then used to simulate the flow inside a hopper with rotating augur. The extrusion pressure in the simulation was compared with the experimental relative power consumption to discharge ratio (pressure) for different rotational speeds. The results for the simulation show good agreements with the experimental pressure values. Based on the results, suggestions were provided to improve the numerical model predictions and the developed numerical model can be used to quantify the extrudability of 3DCP material using either ram-type or rotating screw-type extruders.

Keywords: Extrudability · Rheology · Yield stress · Viscosity · Orifice extrusion · Discrete element modelling

1 Introduction

3D concrete printing (3DCP) is a novel additive manufacturing technique, where a 3D model can be fed into the system and printed layer wise using robots. Due to the free form construction used in the 3DCP method, geometrically complex shapes can be achieved without using high-cost formworks as in conventional construction methods. Because of the elimination of formwork usage in the 3DCP construction technique, cost and wastage can be reduced. Also, as a result of the usage of automation methods such as robot arms for construction, manual labor usage can be reduced. This may result in

reducing human errors, construction hazard and will speed up the construction work [1].

The extrusion-based 3DCP, in which the material should be pumped and extruded through a nozzle in a layer-wise manner, is the commonly used and most efficient technique in construction. The material extrusion and deposition should be continuous without any blockages or segregation. The commonly used term, “extrudability” can be defined as how effectively the material can be extruded fulfilling the above-mentioned criteria. However, extrudability depends on the nozzle size, type of extrusion methods such as ram-type and screw-type, the extrusion speed, and most importantly the rheology of the material. Therefore, extrudability can be effectively defined with respect to the system used for the extrusion, but, for a given system, the material rheology highly affects the extrudability criteria. For example, the material with higher yield stress (i.e. minimum shear stress at the onset of material flow) and higher viscosity (i.e. resistance to flow) have a low tendency to extrude [2]. Also, the ability to form a lubricating layer (a layer consists of finer particles and liquid) between the extruder wall and the flowing material plug may improve the extrudability by minimization of wall friction [3].

Further, the extruded and deposited layers should have enough green-strength to support the vertical stresses induced from the top layers without any failure in addition to its own weight [4, 5]. To fulfill this, the material should achieve higher yield stress after deposition, which is opposite to the requirement for the extrusion process. This is very difficult to achieve and requires a fundamental understanding of the rheology of the material. Therefore, this paper aims to characterize the rheological parameters important for extrusion using a ram extrusion method. Also, a numerical simulation tool was developed using the discrete element method to simulate the ram extrusion and the screw-type extrusion. The developed model can be used in future research to improve the extrudability of 3D printing concrete by improving material rheology as well as the extruder type used.

2 Material Characterization Using Ram Extrusion

The rheology and controlling the rheology play a major role in 3DCP. Therefore, proper rheological characterization should be done using suitable methods. The rheometers widely used to characterize the rheology of normal and self-compacting concrete. However 3D printable concrete has higher stiffness, yield stress, and higher viscosity, hence, rheometers have limitations when implementing high stiff concrete with larger aggregates [16]. Alfani et al. [6] proposed techniques to measure rheology for extrudable cement-based material. The ram extrusion is one of those techniques, where the material is filled inside an extruder barrel and then extruded through a die or an orifice using a ram. The material is extruded at different velocities to obtain maximum steady-state extrusion pressure. The flow curve is developed using the analytical model proposed in Benbow et al. [7] by correlating the extrusion pressure and mean shear velocities. The rheological parameters of extrudable material can then be estimated from the flow curve. The proposed model by in Benbow et al. [7] is based on a uni-axial form of the Herschel-Bulkley model, however, Basterfield et al. [8] and Zhou et al. [9] later developed a specific model to use in an orifice extrusion and given in Eq. (1).

$$P = 2\sigma_0 \ln\left(\frac{D_0}{D}\right) + Ak\left(\frac{2V}{D}\right)^n \left(1 - \left(\frac{D}{D_0}\right)^{3n}\right) \quad (1)$$

Where P , D_0 , D , V are extrusion pressure, barrel diameter, orifice diameter, and material flow velocity at the orifice respectively. σ_0 , k and n are the uniaxial yield stress, flow consistency and flow index parameters (rheological parameters) which define the uniaxial form of Herschel-Bulkley model. A is a constant which defines by the flow index and the maximum convergent angle (θ_{max}) as in Eq. (2).

$$A = \frac{2}{3n} [\sin \theta_{max}(1 + \cos \theta_{max})]^n \quad (2)$$

In the current study, rheological characterization was carried out using the orifice extrusion test and the analytical model shown in Eq. (1).

3 Discrete Element Method (DEM)

Discrete Element Method (DEM) was successfully used in the past to simulate the flow behavior of concrete [10]. The time-stepping algorithm, in which the velocities and accelerations of the particles due to contact forces are considered constant for a small time step. The forces are calculated for the next time step using the displacement of the particles in contact. Further details and theory on DEM simulation technique can be found elsewhere [10, 11].

The DEM model used in this study is a two-phase hardcore-softshell model, where the hardcore (aggregate) is covered with a softshell (cement paste). This type of model is used to simulate the liquid bridge force between two particle contacts or particle wall contacts. Also, the two-phase model reduces the number of particles used in the simulation, hence, it decreases the computational time.

In the current study, Itasca Particle Flow Code (PFC) [12] 2D and 3D versions were used for the simulations. The user-defined particle-particle and wall-particle interactions were implemented in normal particle contact direction and in shear direction separately. The user-defined commands were written in C++ and compiled as a dynamic link library (dll) file to run directly in the software. The Eq. (3), Eq. (4) and Eq. (5) show the force-displacement relationship of particle-particle contacts in normal (particles in compression), normal (particles in tension) and in shear directions respectively. A similar type of force-displacement relationship and DEM model was used by previous researchers to model the SCC and normal concrete flow behavior [11, 13].

$$F_{n,c} = k_{n1} \cdot \text{Max}[0, d_n] \quad (3)$$

$$F_{n,c} = k_{n2} \cdot \text{Max}[0, d_n - d_p] \quad \text{If}; |F_{n,c}| \geq |F_{max,c}|$$

$$\begin{aligned}
F_{n,t} &= F_{n,t-1} - k_{n2}.d_n & F_{n,t} &= \text{Max}[-0.9.F_{max,t}, F_{n,t}] \\
F_{n,t} &= F_{n,t-1} - k_{n3}.d_n & F_{n,t} &= \text{Max}[-F_{max,t}, F_{n,t}] \\
F_{n,t} &= F_{n,t-1} + k_{n4}.(d_n - 0.1.\frac{F_{max,t}}{k_{n3}}) & \text{If}; |F_{n,t}| &\geq |F_{max,t}|
\end{aligned} \tag{4}$$

$$\begin{aligned}
F_{s,t} &= F_{s,t-1} - k_s.d_s \\
F_{s,t} &= F_{s,t-1} - \frac{k_{visc}.d_s}{t} & \text{If}; |F_{s,t}| &\geq |F_{yield}|
\end{aligned} \tag{5}$$

Where, $F_{n,c}$, $F_{n,t}$, $F_{s,t}$ are the normal contact force in compression, normal contact force in tension and shear forces respectively for the considered time step (t). $F_{n,t-1}$ and $F_{s,t-1}$ are the normal tensile force and shear force calculated in the previous time step. d_n is the characteristic normal distance of the two particles, where the positive value means overlapping of particles and negative value denotes the separation of particles (particle distance more than zero). Therefore tensile forces considered to be negative in the expressions. d_p is the paste thickness for the two-phase particle. In the previous equations, k_{n1} , k_{n2} , k_{n3} , k_{n4} and k_s are the contact stiffness values in the considered direction. $F_{max,t}$ and $F_{max,c}$ are the maximum characteristic tensile force and the maximum characteristic compressive force of the particles.

4 Experimental Work

4.1 Materials and Mix

In this study, a printable concrete mix which includes General Purpose (GP) cement, silica fume and graded aggregate (supplied by SIBELCO Australia Ltd.) were used. The silica fume of 110 g was used for 1 kg of cement weight. The graded aggregate can be divided into two categories as coarse aggregate (with 1.18 maximum particle diameter) and fine aggregate (with 600 μm of maximum particle diameter). The coarse graded aggregate used is 560 g per 1 kg of cement. 1.11 kg of fine aggregate was used per 1 kg of cement weight. The water to cement ratio used is 0.23 as a weight ratio. Superplasticizer amount of 0.7 mL per 100 g of binder (cement and silica fume) and retarder amount of 0.4 mL per 100 g per binder also were used in the mix.

The same mixing protocol is followed throughout the experimental procedure. Initially, the dry mix consists of cement, silica fume and aggregate were mixed in a 5 L Hobart mixer around 3 min at low speed (speed 1). Afterward, water was added gradually and mixing was done around 1 min at low speed. Finally, the superplasticizer and retarder were gradually added (while mixing) and the high shear mixing (speed 2) was done around 5 min.

4.2 Rheology Characterization

Rheology characterization of the mix was carried out using a custom made ram extruder. The material was extruded through an orifice using displacement rates varying from 0.1 mm.s^{-1} to 4 mm.s^{-1} . The barrel diameter (D_0) used in the extruder is

200 mm and the orifice diameter (D) used is 40 mm. The barrel height is around 450 mm and can accommodate a large amount of material. Therefore, the test setup gives the advantage of conducting several trials of extrusion with only using a single fill of the material inside the extruder.

Initially, the material was filled up to around 400 mm level and compaction of the material was done using a steel rod to remove the entrapped air. Using the piston (ram) attached to a 50 kN MTS testing system, the material can be extruded through the orifice using different displacement rates. It should be noted, that the test was initiated with the highest displacement rate to the lowest displacement rate to avoid the liquid phase migration reported in previous literature [14, 15] at lower displacement rates. Test for a considered displacement rate can be stopped when a steady piston force (steady-state) achieved in the force vs. time or force vs. displacement curves. Afterward, the test can be continued for a different displacement rate.

Three trials were conducted for each ram displacement rate and the average steady extrusion force was calculated. The extrusion force was converted to extrusion pressure considering the piston cross-sectional area. The piston driving velocity was converted to material flow velocity (V), considering the mass conservation. The extrusion pressure vs. mean shear rate plot was shown in Fig. 1. With the least square error method, the analytical model given in Eq. (1), was fitted to experimental data to achieve the rheological parameters given in Fig. 1.

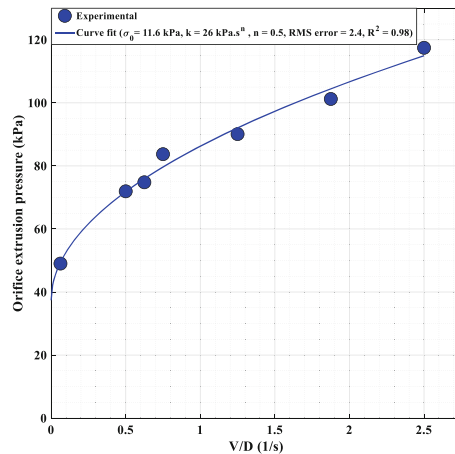


Fig. 1. Orifice extrusion pressure vs. mean shear rate

4.3 Screw Type Extrusion and Power Consumption Measurement

A screw-type extruder (used in a gantry print system at Swinburne University of Technology) was used to quantify the extrudability of the material. Burbidge et al. [17] and Botten et al. [18] explain the method to estimate the extrusion pressure gradient in

a hopper (i.e., along the material flow direction) for single-screw extrusion from the rheological parameters characterized in ram extrusion.

In the current study, the measurement of power consumption was done for different screw rotational speeds to find the relationship between the rheological parameters characterized in ram extrusion and the relative power (δP) measurements. A power measurement source can be installed between the power supply and the printer to monitor the power consumption. Initially, power consumption measurements were done at different speeds (from 0.5 rev.s^{-1} to 2.5 rev.s^{-1}) of screw rotations without any material inside the hopper. Afterward, the power consumption measurements were done for different speeds with the material inside the hopper. The material inside the hopper kept at a constant level and the print head kept stationary without any movement. The power consumption difference with and without material was recorded as the relative power consumption. Additionally, the discharge rates (Q) of the material also were recorded for different screw rotational speeds.

The relative power consumption and discharge rate of the material for different screw rotational speeds are shown in Fig. 2. The relative power consumption increases with rotational speed showing a power-law relationship. The discharge rate increases linearly with the increasing rotational speed.

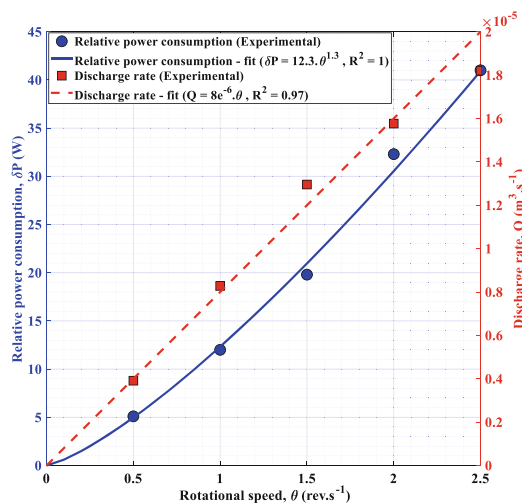


Fig. 2. Relative power consumption and discharge rate variation for different screw rotational speeds

5 Numerical Simulation

5.1 Orifice Extrusion

The orifice extrusion experimental results were used to calibrate the numerical model. DEM 2D simulations were used to reduce the computational time. Mono size particles were selected similar to the maximum particle size (particle diameter) used in the experimental (i.e., 2 mm approximately). The initial characteristic distances were selected using the analytical models developed by Mikami et al. [19].

In the current simulation, particles were generated inside the extruder barrel (without any overlapping) until the system reaches approximately a target porosity of 0.1. This is similar to the experimental porosity value calculated at the beginning of the extrusion test. Afterward, gravity is activated to achieve equilibrium. At the particular stage, orifice was covered with a wall to prevent the particles from falling from the bottom. Afterward, the piston was moved similar to the constant velocities used in the experimental procedure and the piston force was recorded.

The experimental ram force at the lowest piston driving velocity was matched to the numerical piston driving force at the particular velocity to calibrate the characteristic forces $F_{max,t}$ and $F_{max,c}$. Afterward, the simulations were conducted for other piston velocities and the force vs. velocity values were plotted for experimental and numerical simulations. In order to match both gradients, the k_{visc} the value was adjusted. Table 1 provides the calibrated DEM model parameters.

Table 1. Calibrated DEM parameters using orifice extrusion simulation (particle-particle interaction)

Parameter	Value	SI unit
$F_{max,t}$	2	N
$F_{max,c}$	2	N
F_{yield}	1×10^{-2}	N
k_{n1}	7	Nm^{-1}
k_{n2}	1×10^5	Nm^{-1}
k_{n3}	333	Nm^{-1}
k_{n4}	200	Nm^{-1}
k_s	1×10^3	Nm^{-1}
k_{visc}	10	Nm^{-1}
d_p	1×10^{-4}	m
Friction coefficient	1×10^{-2}	—
Particle density	220	kg.m^{-3}

The comparison of the numerical steady-state extrusion force and the experimental extrusion force values for different piston driving velocities are shown in Fig. 3.

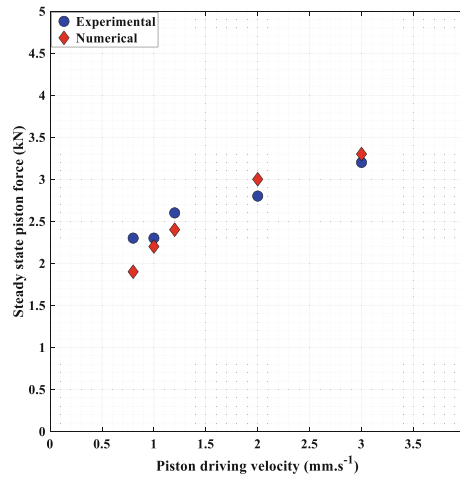


Fig. 3. Experimental and numerical ram force comparison

From Fig. 3, it can be seen that the numerical ram forces and experimental ram forces are similar after the calibration process. The maximum difference between experimental and numerical ram force is around 15%.

5.2 Screw Type Extrusion Simulation

Using the calibrated model from the orifice extrusion, the screw-type extrusion was simulated with different rotational speeds. The particle size was increased by two times for the 3D simulations to reduce the computational time. A proportional parameter was incorporated to increase the calibrated forces and the stiffness values as mentioned in [11]. Figure 4 shows the modeled screw extruder geometry similar to the one used in the experimental work.

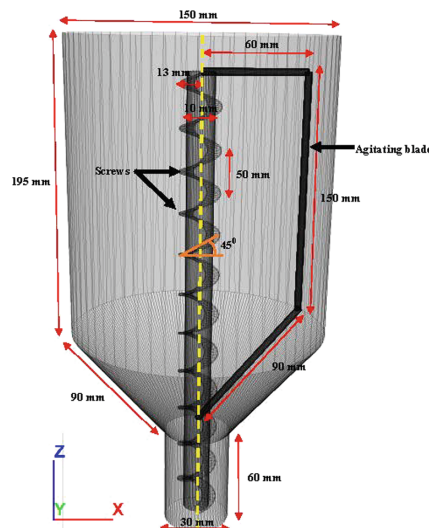


Fig. 4. Screw extruder geometry in the simulation (as used in experimental work)

In the simulations, the downward push force applied by the extruder was recorded to compare with the experimental $\delta P/Q$ value (which can be correlated with extrusion pressure in a screw-type extrusion). Figure 5 (a) shows the variation of vertical screw force with time for different rotational speeds (flow direction is negative z-direction). In this preliminary study, the average extrusion force exerted by the screw (in the negative z-direction) at steady-state is considered and shown in dotted straight lines in Fig. 5 (a). With the available computational capacity (3.4 GHz clock speed and 16 GB RAM), for small rotational speeds such as 1 and 1.5 rev.s^{-1} , the initiation of extrusion of the material was considered.

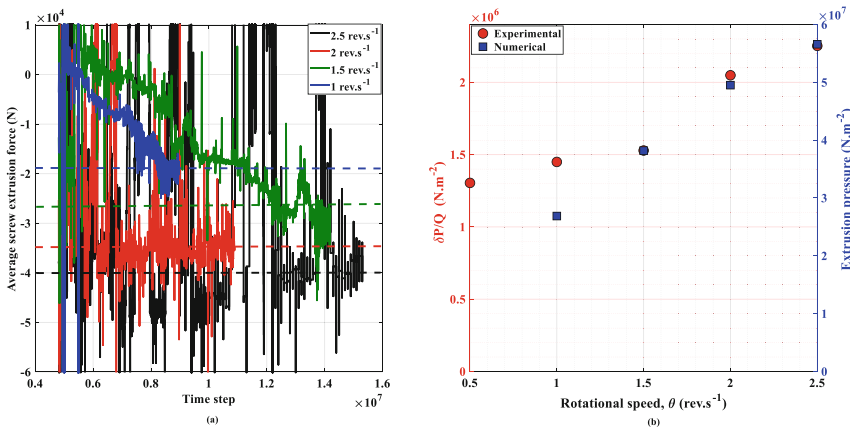


Fig. 5. (a) Numerical extrusion force variation for different rotational speeds. (b) Comparison of experimental and numerical extrusion pressure values

Figure 5 (b) shows the comparison of the experimental $\delta P/Q$ value and the numerical extrusion pressure value (extrusion force/cross-sectional area of the nozzle). As seen in Fig. 5 (b), both the experimental and numerical pressure values show a similar trend (increasing pressure with increasing rotational speed), however, the numerical pressure values are higher than the experimental pressure values ($\delta P/Q$). The possible reasons may be the higher particle sizes used and the mono-sized particles used in the simulations. The forces from the agitating blade also should have a contribution to the power-consumption in experimental results. Therefore, in future research, the particular component also should be considered. Finally, it can be concluded, that there should be a direct link between the rheological parameters obtained from orifice extrusion test and the extrudability of cementitious material in a screw-type extruder.

6 Conclusions

Preliminary studies were done to characterize the extrudability of 3DCP in the current work. DEM was used as the numerical simulation method for the purpose. The following conclusions can be made from the study.

- Relative power consumption increases with the increasing rotational speed giving a power-law relationship between the two parameters (in a screw-type extruder). Relative power measurements can be used as an effective method to characterize the extrudability of different mixes.
- The material discharge rate increases linearly with the rotational speed in a screw-type extruder.
- Ram extrusion can be effectively used to characterize the rheological parameters of 3DCP material. Also, it can be used to calibrate the DEM numerical model.
- The DEM two-phase model can be used effectively to simulate the ram extrusion forces. The developed model can be used in other flow simulations such as screw-type extrusion as well. Therefore, the developed tool is useful in quantifying extrudability and also to design screw-type extruders for 3DCP applications.

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Investigation on Structural Build-Up of 3D Printable Foam Concrete

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Abstract. Over the last decade the use of foam concrete in the construction industry has become popular due to its high thermal and acoustic insulation capacity in combination with sufficient strength characteristics. The use of foam concrete in 3D printing (3D Foam Concrete Printing) is a perspective approach which should enable automated freeform construction without formwork and at the same time would contribute to sustainability and energy efficiency of the structures. Since 3D-printing requires very specific rheological properties of foam concrete in its fresh state, a systematic research on this subject is needed. For this purpose, foam concrete mixtures containing more than 35 vol% protein-based foam and fresh density of approx. 1200 kg/m^3 were developed and investigated with respect to their suitability for 3D printing by extrusion-based selective material deposition. Constant shear rate rheometer tests were performed to determine static yield stress and critical strain at flow onset at concrete ages of 30 min to 150 min, the time interval specifically relevant for the 3D printing process. Finally, the estimation of structural build-up was verified by manufacturing 800 mm long foam concrete walls until their collapse.

Keywords: 3D-printing · Foam concrete · Rheology · Digital construction · Thixotropy

1 Introduction

Formwork-free digital concrete (DC) construction methods such as 3D concrete printing have showed their high potentials for increasing productivity on the construction site [1–4]. The variety of the research topics, challenges and opportunities in the context of DC was well summarised in [5]. The research at hand focusses on a novel approach of using foam concrete in extrusion-based 3D printing.

Foam concrete (FC) is a lightweight material, which can be produced by pre-foaming or mixed foaming [6] with a range of densities down to 400 kg/m^3 [7, 8]. As a result of its low density, FC yields high thermal insulation capacity. Typical characteristics of modern foam concretes are reported in [8, 9].

The variety of foaming techniques and methods for intermixing the foam into the cement-based matrix enables the production of foam concrete to be adapted for a continuous DC processing. Some production techniques for printable foam concrete and feeding systems for 3D printing are described in [10]. The concept of mixture

design for printable foam concrete was developed in the framework of the CONPrint3D-Ultralight® project; the obtained print experiments proved the possibility of additive fabrication with foam concrete [11]. In a further research at the TU Dresden, printable foam concrete with density as low as 860 kg/m³ and compressive strength of 2.5 MPa at an age of 14 days was produced [12].

The research at hand deals with rheological properties of printable foam concrete. The main rheological characteristics of fresh FC – static and dynamic yield stresses, modulus of elasticity and structuration rate – were determined by means of constant shear rate (CSR) test on foam concretes made of different raw materials. To estimate the maximum numbers of layers which can be deposited on upon other before structural failure of the wall occurs, we assumed that the collapse takes place due to the deformation in the first wall layer upon reaching static yield stress, thus, neglecting buckling propensity. Therefore, for prediction of the critical number of printed layers, the theoretically estimated static yield stress in the bottom layer was compared to the static yield stress defined by a rheometry test. The influence of the geometrical factor α_{geom} described in [13, 14] was neglected. Furthermore, the predicted buildability of FC was compared to the actual printing test results. To ensure comparability, the rheological measurements were performed simultaneously with the printing experiments on the same FC batches.

2 Experimental Program

2.1 Materials and Mixture Proportions

Table 1 presents compositions of the investigated foam concretes. The binder of all compositions contains a type II Portland composite cement CEM II/A-M (S-LL) 52.5 R (OPTERRA Zement GmbH, Werk Karsdorf, Germany) and hard coal fly ash Steamant H-4 (STEAG Power Minerals GmbH, Dinslaken, Germany). As further pozzolanic additives silica fume (Grade 971U, Elkem ASA Silicon Materials, Skøyen, Norway) and aluminosilicate (Centrilit NC II, MC-Bauchemie GmbH & Co. KG, Bottrop, Germany) were used. The chemical composition of the materials is given in Table 2.

A protein-based foaming agent (Oxal PLB6, MC-Bauchemie GmbH & Co. KG, Bottrop, Germany) was diluted with water in the ratio 1:30 (by volume) and then utilized for production of the foam with an average density of 60 kg/m³. Technical characteristics of used foam generator and settings for production of foam are described in [12]. Polycarboxylate ether-based superplasticizers MasterGlenium SKY 593 (BASF Construction Solutions GmbH, Trostberg, Germany) and MC-PowerFlow 5100 (MC-Bauchemie Müller GmbH & Co. KG, Bottrop, Germany) were used for achieving the required workability and reducing the water content.

Table 1. Mixture compositions in accordance with design guidelines for printable foam concretes in [11]. The percentages of the total volume in the binder are shown in brackets.

Material	M-A1	M-A2	M-A3
Cement [kg]	626 (60 vol%)	559 (55 vol%)	564 (55 vol%)
Fly ash [kg]	297 (40 vol%)	290 (40 vol%)	292 (40 vol%)
Water [l]	251	288	275
Superplasticizer [l]	0.002	0.0027	0.002
Silica fume [kg]	–	37 (5 vol%)	–
Alumosilicate [kg]	–	–	43 (5 vol%)
Foam [l]	41	38	39
FC (w/z) _{eq}	0.37	0.44	0.41
Design density [kg/m ³]	1200	1200	1200
Plastic density after extrusion [kg/m ³]	1140	1066	1246

Table 2. Chemical composition of raw materials used for FC (LOI: loss on ignition, n.d.: not determined).

Material	Density [g/cm ³]	Chemical composition [% by mass]											
		Residue	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	LOI	CO ₂	CL
Cement	3.12	0.74	20.63	5.35	2.82	60.9	2.14	3.52	1.05	0.22	3.47	2.8	0.07
Fly ash	2.22	n.d.	n.d.	n.d.	n.d.	3.6	n.d.	0.6	n.d.	2.9	1.8	n.d.	0.01
Al ₂ SiO ₅ *	2.61	n.d.	51.2	44.9	n.d.	n.d.	n.d.	n.d.	1.0	n.d.	n.d.	n.d.	n.d.
Silica fume	2.29	n.d.	98.4	0.20	0.01	0.20	0.10	0.10	0.20	0.15	0.50	n.d.	0.01

*Alumosilicate

2.2 Mixture Preparation

The mixing of the components took place in the cone mixer KKM 30L [15]. The mixture was designed for a total volume of 30 L. The mixing process was subdivided into two steps: (1) mixing of the cement-based matrix and (2) intermixing of the pre-fabricated foam into the cement-based matrix. At first, dry materials were homogenized for 2 min with an engine speed of 3000 rpm. Subsequently, water and superplasticizer were added, and the mixing was resumed for further 2 min at the same speed. In the next step, the speed was reduced to 1500 rpm and the separately prepared foam was gradually added. To avoid damage to the foam structure caused by overexposure to mechanical stirring, the mixing time for each portion of the foam was kept below 30 s. The blending of the foam took in total 5 min.

2.3 Rheometry

HAAKE MARS II Rheometer was used with building materials cell and vane configuration. Temperature of the samples was maintained at 20 °C during testing.

Determination of Bingham parameters was conducted as follows: 10 rotational steps from 0.1 s^{-1} to 10 s^{-1} in 30 s, rotation at 10 s^{-1} for 30 s, 15 rotational steps from 10 s^{-1} to 0.1 s^{-1} in 45 s. This stage was also used as pre-shear, which was performed to ensure similar state of the samples before static rheological measurements.

Static yield stress (SYS) values were determined by means of CSR test [16, 17] using single-batch approach [18]. Test duration was set to 240 s; each SYS measurement was manually interrupted when the peak values of shear stress were reached. In order to study the effect of CSR on the obtained values of the SYS, different CSRs of 0.08, 0.12, 0.15, and 0.18 s^{-1} were applied. Structuration rate was estimated using Roussel's model [19].

2.4 The 3D Printing Process

3D printing with the designed mix compositions was conducted using custom developed 3D printing testing device (3DPTD) earlier described in [11]. 3DPTD was equipped with a progressive cavity screw and a rectangular nozzle with an opening of $14 \text{ mm} \times 33 \text{ mm}$. The printhead was moving at a constant speed of 40 mm/s . Straight wall specimens with a length of 800 mm were produced with layer-to-layer deposition time intervals (TI) of 2 min, 5 min and 10 min. Deposition of the layers was aborted after collapse of the wall specimens or inability to print because of, e.g., overstiffening of the material. The number of printed layers before the occurrence of noticeable deformations and collapse of the wall was recorded.

3 Results and Discussion

3.1 Bingham Parameters

Figure 1 presents the dynamic yield stress values for three different foam concretes. In comparison to the composition M-A2 with dynamic yield stress of approximately 320 Pa, composition M-A1 demonstrated higher dynamic yield stress of 355 Pa, while the highest dynamic yield stress of 388 Pa was observed for composition M-A3. These differences can be traced back to the various composition of the binder used. According to the results in Fig. 1, composition M-A2 is more suitable for pumping since its plastic viscosity (approximately 6.4 Pa s) is lower than for compositions M-A1 and M-A3 (approximately 9.6 Pa s). On the other hand, to assure shape stability just after extrusion, higher dynamic yield stress is advantageous [20]. This opportune characteristic is attributive to composition M-A3.

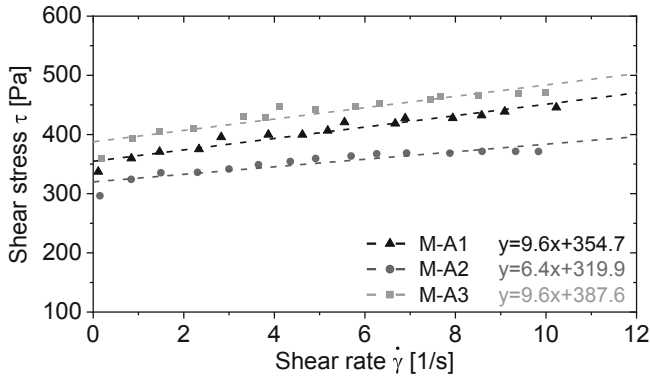


Fig. 1. Flow curves of the foam concrete under investigation.

3.2 Selecting Constant Shear Rate for Static Yield Stress Measurements

Figure 2 illustrates the effect of the applied CSR on the shear stress development over time for the foam concrete composition M-A1 at the age of approximately 40 min after adding water. It is worth noting that different testing times were required to reach the peak values by applying different shear rates on the foam concrete sample. It could be also observed that the value of the SYS depends on the shear rate used in the experiment, while the maximum value of shear stress could be reached faster by applying higher shear rate.

During pumping and deposition of the foam concrete layers, the material is sheared most intensively. However, after deposition, foam concrete layers remain mainly in a resting state, which leads to the inference that the material should be tested at a lowest possible CSR to simulate this static condition. Experimental results showed that by applying CSR of 0.08 s^{-1} even at the age of 150 min after water addition, flow onset could be reached within a reasonable testing time of 180 s. Considering this result and the findings in [17], CSR of 0.08 s^{-1} was chosen for further investigation.

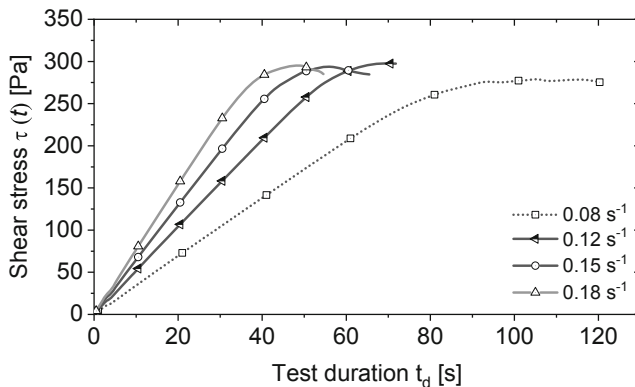


Fig. 2. Influence of the applied constant shear rate on the development of the shear stress over the time of the foam concrete sample M-A1.

3.3 Structuration Rate

Figure 3 shows the development of the shear stress of composition M-A1 with time after water addition. $\text{SYS } \tau_0$ increased with the resting time t_{rest} , while shear strain γ decreased. Compositions M-A2 and M-A3 demonstrated a similar dependence of the SYS on resting time. It was also determined that shear elastic modulus $G(t)$ increased with a magnitude corresponding to the τ_c and t_{rest} values.

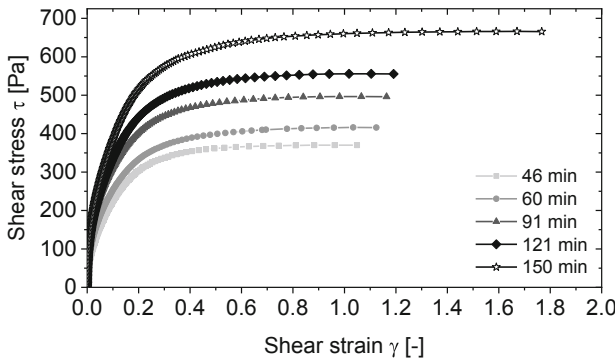


Fig. 3. Shear stress-shear strain curves for composition M-A1 at various times after mixing.

Within the investigated period, all three foam concrete compositions exhibited linear growth in SYS over time, which complies to Roussel's model described in [19]; see Fig. 4. The slope of the dashed lines gives a value of the structuration rate of the material, also referred to as A_{thix} . Compositions M-A2 and M-A3 showed structuration rate of 4.6 Pa/min and 4.9 Pa/min, respectively, which is pronouncedly higher than the structuration rate of 2.7 Pa/min as seen with composition M-A1. Obviously, very fine pozzolanic additives silica fume and aluminosilicate in compositions M-A2 and M-A3, respectively, accelerated the flocculation/hydration processes.

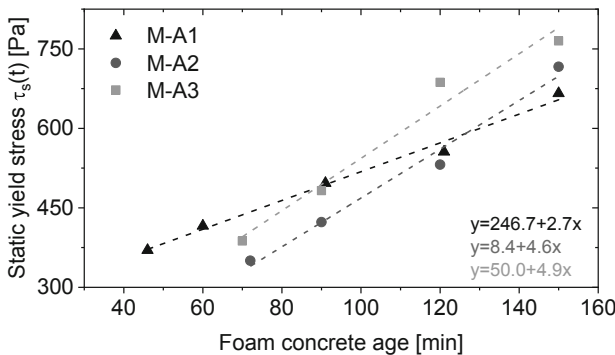


Fig. 4. Development of the static yield stress in time.

It should be noted that the material behaviour was only investigated within the first 150 min after water addition. Eventually, a shift from linear to exponential development of the structuration rate is expected with progressing hydration. Using A_{thix} values, the building rate of foam concrete walls, at which layers can support themselves and the weight of subsequent layers, could be determined; see Sect. 3.5.

3.4 Printing Test

All three foam concrete compositions could be extruded and deposited in layers. However, printing characteristics of each composition differed. Thus, for all examined foam concrete wall specimens with TI of 2 min, approximately 7 layers could be printed before noticeable deformations and final collapse of the wall specimen occurred.

With TI of 5 min, none of the wall specimens collapsed. The critical number of layers could not be reached because of overstiffening of the material. It is worth noting that blockage of the nozzle did not occur, rather the surface quality decreased and certain discontinuities in the printed layers appeared. Figure 5 depicts the printed wall specimen with foam concrete M-A1 consisting of 25 layers. The last layer was printed at the age of 247 min after water addition. Thus, the entire printing of the wall specimen took 135 min. It could be seen that the surface quality of the layers decreases with the increase in wall height; see Fig. 5b. Using compositions M-A2 and M-A3, 16 and 14 layers, respectively, could be printed, until the experiment was stopped.

Wall specimens produced with TI of 10 min suffered from the pronounced stiffening of the mixture. With the composition M-A1, only 15 layers could be printed, while the number decreased to just 7 layers for the compositions M-A2 and M-A3.

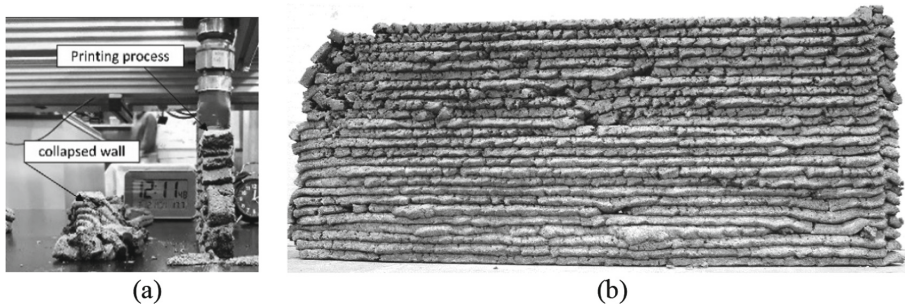


Fig. 5. 3D printing of the foam concrete M-A1: (a) collapsed wall with TI of 2 min and upright standing wall being printed with TI of 5 min TI ; (b) foam concrete wall specimen printed with TI of 5 min.

3.5 Comparison of the Theoretically and Experimentally Obtained Results

By applying the foam concrete density ρ , measured directly after extrusion, layer height h , defined by nozzle shape, and gravity constant g in Eq. (1), the theoretical SYS in the bottom layer can be calculated by:

$$\tau_0 = \frac{\rho g h}{\sqrt{3}} \quad (1)$$

Subsequently, the theoretical SYS in the bottom layer depending on the number of printed layers was computed using Eq. (2):

$$\tau_{0,f} = \frac{\rho g H_m}{\sqrt{3}} \quad (2)$$

where H_m is the height of the wall specimen. The required SYS depending on the number of printed layers can be expressed with:

$$\tau_{0,f} = \tau_0 + A_{thix} \cdot TI \cdot (n_t - 1) \quad (3)$$

where τ_0 is initial critical SYS, A_{thix} is structuration rate of the material, TI is time interval between layers, and n_t is total number of printed layers. Note, that in Eq. (3), time for printing of the single layer, which depends on the printing velocity, is ignored, since it is negligibly small in comparison to the duration between printing of subsequent layers.

Figure 6 presents the results of the theoretically determined required yield stress in the bottom layer for printing the wall specimen using composition M-A1 and effective yield stress in the bottom layer by applying experimentally determined rheological parameters in Eq. (3).

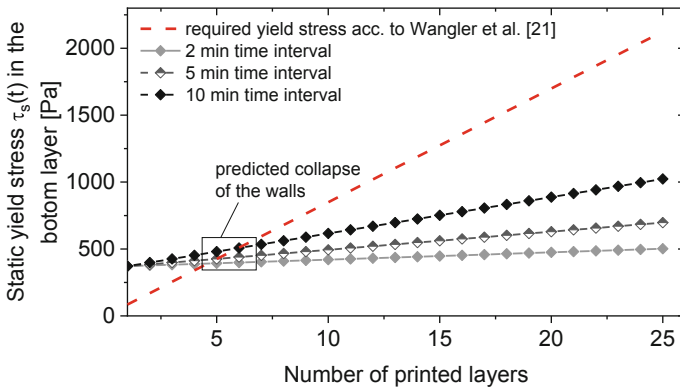


Fig. 6. Prediction of the foam concrete wall stability based on a theoretical calculation and a calculation using experimentally determined rheological parameters; results for the foam concrete M-A1.

The intersection of the red-dashed line acc. to Eq. (2) with other lines shows when the theoretical threshold of the SYS is reached and structural collapse is to be expected. Therefore, for a wall printed with TI s of 2 min and 5 min, critical deformations leading to the collapse of the wall should be reached at layer number 5. Whereby, by extending the TI to 10 min, collapse of the wall is expected after the printing 7 layers. It is worth noting that theoretical calculation using Eq. (2) and calculation using Eq. (3), which contains experimentally determined rheological values, differ from the results gained by the direct printing test. Hypothetically, this discrepancy occurred due to different drying kinetics of the material in the rheometer cell and during the printing experiment. In the case of foam concrete, this effect can be more pronounced owing to its higher pore surface area in comparison with conventional concrete. Only the prediction for the wall specimens with TI of 2 min is in accordance with the results of the 3D printing test.

The results for compositions M-A2 and M-A3 differ from composition M-A1 in the first stage, in the initial value of the SYS and correspondingly different slope of the functions. However, discrepancy of the predicted maximum number of layers and de facto printed number of layers differ in the same range as with composition M-A1.

4 Conclusion

Key rheological properties of printable foam concrete were reported and the effects of substituting the cement with silica fume and aluminosilicate were quantified. The foam concrete compositions M-A2 and M-A3, which contained silica fume and aluminosilicate, respectively, yielded higher structuration rate than the reference mixture M-A1. In essence, all three foam concretes under investigation showed promising rheological behaviour with regard to 3D printing. However, foam concrete composition M-A3 with the addition of aluminosilicate showed the highest structuration rate, likewise the highest dynamic yield stress, which are essential for retaining the form stability after extrusion. A further finding was that the theoretical approach for prediction of the structural collapse by use of experimentally determined rheological parameters underestimated the wall stability according to the 3D printing test results. Future studies on printable foam concrete should be extended on clarifying this phenomenon as well towards analysis of the reproducibility of the experimentally derived rheological parameters.

Acknowledgements. This work was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation), Project Numbers 387152958 and 387095311, within the priority program SPP 2005 OPUS FLUIDUM FUTURUM – Rheology of reactive, multiscale, multi-phase construction materials.

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Effect of Cement Type and Limestone Powder Content on Extrudability of Lightweight Concrete

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Abstract. Extruded lightweight aggregate concrete (LAC) enables to unite static and building physics properties within monolithic structures. Besides, material demand can be reduced according to necessity. However, the contradicting requirements in extrusion for pumpability and buildability are intensified compared to normal concrete due to the change of LAC fresh properties during pumping. This paper focusses on the effect of cement type and amount of limestone powder on the pumpability of LAC at comparable buildability. We show that the pumping performance enhances with increasing limestone powder content. Furthermore, we find that the increase in density during the pumping process is affected by the water retention of the material, which in turn correlates with the limestone powder content. The resulting strength can thus be consciously improved. The amount of limestone powder has only a minor effect on structural build-up and static yield stress and thus, on buildability. However, we find a general strong increase in static yield stress during pumping of LAC, which further facilitates the buildability in addition to the positive effect of the low density of LAC resulting in reduced weight loads to bear during extrusion. Another advantage is that reasonable replacement of cement by limestone powder leads to less drying shrinkage without significantly reducing the strength. Concluding, the requirements for extrusion of LAC – for both pumpability as well as buildability – can be fulfilled and adjusted to necessity by partly substitution of the cement with limestone powder.

Keywords: Additive manufacturing · Extrusion · Rheology · Lightweight aggregate concrete · Limestone powder · Pumpability

1 Introduction

In the last decade, additive manufacturing (AM) such as extrusion of concrete has taken place to a remarkable extent. The potential and the advantages of this technology have been shown, e.g. by [8]. Beside others, main benefits are the elimination of framework, great design freedom, target-oriented use of material and consequently the reduction of waste.

We aim to combine the technology of additive manufacturing with the benefits of lightweight aggregate concrete (LAC). Lightweight aggregate concrete enables to unite static and building physics properties in one material without the need of additional insulation. Its low density results in better thermal insulation properties and less introduction of weight into the system than with normal concrete. In combination with extrusion, e.g. exterior wall elements can be further improved with regard to thermal insulation by the installation of closed air chambers or by geometrically avoiding thermal bridges as described in [1].

The critical factors for extrusion are pumpability and buildability. Buildability in that sense describes the ability to retain its shape and withstand the weight of subsequent layers. According to Roussel [6] the requirements for buildability are that the lowest layer has a sufficient yield stress τ_0 to bear its dead weight and that in combination with the structural build-up A_{thix} as the increase of yield stress with time at rest $\tau_0(t)$, the bearable stress is higher than the applied stress of the subsequent layers. The applied stress is calculated by the product of density ρ , gravity g , height in dependence of time $h(t)$ and a geometrical factor α_{geom} . Thus, the equation writes $\tau_0 + A_{thix}t \geq \rho gh(t)/\alpha_{geom}$ to avoid plastic failure of the component [6]. Furthermore, buckling failure can occur, but is not further discussed in this paper as it is dependent on the geometry.

Comparing the extrusion of LAC to normal concrete extrusion, the pumpability of LAC imposes greater challenges as the lightweight aggregates are porous and can absorb water during the process. This might lead to changing properties of the LAC under pressure [3]. In terms of buildability, on the other hand, the requirements are easier to fulfill than with normal concrete as the density of the LAC is significantly lower than of normal concrete. Therefore, each layer induces less weight on the system and the minimum required strength of the lowest layer does not have to increase as quickly.

The aim of this paper is thus to analyze and identify key parameters to enhance the pumpability of LAC while maintaining a comparable buildability. In former research [3] we found that the pumpability of LAC depends on the apparent viscosity and the limestone powder content of the mixture. Based on this, we first vary the fineness of Ordinary Portland Cement (OPC) and combine it with a partially substitution of the cement with suitable limestone powders. We analyze the rheology as well as the time dependent strength development of the pastes and thus, their suitability for extrusion (see Sect. 3.1). Furthermore, we investigate concretes in terms of their pumpability and buildability varying the limestone powder content (see Sect. 3.2). Besides, we analyze the change in density, which occurs during pumping and its effect on buildability (see Sect. 3.2).

2 Materials and Methods

2.1 Materials

The concretes' binder were based on OPC. Three cements varying in fineness were tested for their suitability for this project: CEM A with a specific surface $A_{Blaine,A} = 2,700 \text{ cm}^2/\text{g}$, CEM B with $A_{Blaine,B} = 3,500 \text{ cm}^2/\text{g}$ as well as CEM C with

$A_{\text{Blaine,C}} = 5,600 \text{ cm}^2/\text{g}$. The peculiarity of the examined cements is that they have the same chemical composition and were manufactured in the same factory. Both, the cement properties such as compressive strength as well as the rheological properties of the cement paste were an evaluation criterion (see Sect. 3.1).

Furthermore, the cement was partly replaced by equal volumes of limestone powder (LP). In order to determine the influence of the LP, the same amount of five types of LP of different chemical composition was chosen. They differed, e.g. in clay content and the fineness varied between $d_{50} = 2.2 \text{ }\mu\text{m}$ and $15.1 \text{ }\mu\text{m}$. Table 1 shows the particle sizes of the OPC and the LP considered. For comparable rheological properties a polycarboxylate ether (PCE) based superplasticizer was added. Furthermore, we used silica fume with $d_{50} = 0.15 \text{ }\mu\text{m}$ to increase the packing density. The amount was kept constant for all mixtures.

Table 1. Average particle sizes of the OPC and LP considered.

	CEM A	CEM B	CEM C	LP1	LP2	LP3	LP4	LP5
$d_{50} \text{ [}\mu\text{m]}$	24.3	15.2	7.9	15.7	7.1	3.3	3.3	2.2
$A_{\text{Blaine}} \text{ [cm}^2/\text{g]}$	2,700	3,500	5,600	3,7000	6,7000	9,200	8,200	11,400

In the course of the investigations, a special cement (CEM D) was additionally developed based on the results with the different types of OPC and LP. The aim was to integrate the knowledge from the laboratory tests into cement production.

For the lightweight aggregate concrete expanded glass granulate with a maximum grain size of 2 mm was used. The particle size distribution of the lightweight aggregates as well as the water content – mixing water and suction water – was kept constant for all experiments.

2.2 Mix Design and Investigated Test Series

All mixtures contain paste with cement, silica fume and a water/binder ratio of 0.38 by mass. The concrete composition consists of 47 vol.% paste and 53 vol.% aggregates. The replacement of the cement by limestone powder and the amount of PCE was adapted according to the investigations. In a first step, we investigated the influence of the cement type by variation of the fineness of OPC: three types of cement (CEM A, CEM B and CEM C) were considered (see Sect. 2.1). CEM C was chosen for the further experiments (see Sect. 3.1).

Second, we analyzed the effect of five different LP types as described in Sect. 2.1. CEM C was in each case substituted by the same amount of LP and the PCE was adapted to reach a slump flow of $190 \pm 15 \text{ mm}$ at 15 min after water addition. We analyzed the fresh and the hardened properties of the paste to select a suitable mixture for extrusion. The aim was to have a low apparent viscosity for good pumpability as described in Sect. 1, as well as high yield stress and structural build-up for good buildability and high strength for an enhanced load bearing capacity of the hardened concrete structure. Consequently, LP1 was chosen for further tests.

Third, we analyzed the pumpability and the effects during pumping on concrete taking into account different amounts of the selected LP1 (0 vol.%, 20 vol.% and 40 vol.%) in combination with CEM C. The objective is to evaluate the advantages and disadvantages of the dosage of LP considering pumpability and buildability. Furthermore, the difference between those mixtures and the industrially produced special cement CEM D was analyzed. The density of the lightweight aggregate concretes was in average $1,190 \pm 10 \text{ kg/m}^3$.

2.3 Mixing Regime and Test Setup

We examined the LAC compositions rheologically and with regard to their pumpability. All tests were conducted at laboratory atmosphere at $20 \pm 1 \text{ }^\circ\text{C}$ and $65\% \pm 5\%$ relative humidity.

Mixing Regime. We kept a uniform mixing order to eliminate confounding effects:

- Mix dry aggregate and suction water (pre-wetting): 1 min
- Rest period (water absorption): 4 min
- Add cement (and if applicable limestone powder): 1 min
- Add mixing water and PCE, mixing: 45 s
- Open mixer and scratch out concrete for homogenization purposes: 1 min
- Further mixing: 45 s

Dynamic Measurements. Following a 1 min remix (at 11 min after water addition) to break a potentially formed inner structure of the material, the determination of the rheological properties began 14:45 min after addition of water to the cement. Therefore, we used a rotational rheometer (Viskomat NT) and a vane-in-cup measuring device with a six-bladed vane paddle (height 60 mm and radius 20 mm). We measured the torque values in eighteen descending rotational speed steps from 80 rpm to 0.08 rpm with 8 s each. To analyze the apparent viscosity η , we used the equilibrium torque value of the speed steps 50 rpm, 40 rpm, 30 rpm, 20 rpm, 15 rpm, 12.5 rpm, 10 rpm and 7.5 rpm. Calculation of the shear rates for the responding rotational speeds was done on basis of the second Krieger solution (Plug Flow) and the calculation of the apparent viscosity (at a shear rate of 25 1/min according to [4]) with the Herschel-Bulkley approach. The other steps must be neglected, because not every concrete showed equilibrium values in these steps. Each test was repeated at least two times and average values were built.

Static Measurements. Besides the dynamic measurements, static rheological measurements were conducted on the fresh concrete (approx. 15 min after water addition) and after the pumping procedure (approx. 25 min after water addition). The mixtures were pre-sheared for 85 s to break inner structures. Thereafter periods of rest (30 s, 60 s, 120 s, etc.) and 6 s long periods of shear (0.15 rpm) took turns. The peak torque value in the shear period was recorded and the static yield stress was determined.

Pumpability Measurements. The results of the rheometer were compared to real pump tests. The designed mixtures were pumped in the actual 3D printer setting. We used an eccentric screw mortar pump with a diameter of 90 mm with a frequency

controlled motor speed. Thereupon, we pumped the material through a mortar hose with 25 mm inner diameter and a length of 5 m. Before every examination of the pumpability, the pump and hose were wetted with water in order to ensure a uniform lubrication of the wall. The mortar pump was always activated at a control frequency of 7.3 Hz and the flow rate was determined three times. Afterwards, the frequency was accelerated to 15.6 Hz and the flow rate determined again. Finally, for some mixtures, the flow rate was also determined at a frequency of 26.2 Hz. The mean value of the flow rates was used for further evaluation and comparison. During the complete pumping procedure, the pressure was recorded automatically in the hose directly after the pump. Furthermore, the density of the fresh lightweight aggregate concrete according to EN 1015-6 and the concrete temperature were measured before and after pumping.

Hardened Material Properties. Casted prisms were produced from the material after mixing and, in case of the concretes, after pumping. They were compacted on a vibrating table and stored in the climate chamber at 20 ± 1 °C and $65\% \pm 5\%$ relative humidity until they were tested. The flexural and compressive strength was evaluated according to the standard EN 196-1.

3 Results and Discussion

3.1 Paste

A variation of the fineness of OPC combined with a partial substitution of the cement by limestone powders with varying fineness and chemical composition was evaluated in terms of rheology and hardened material properties.

As described in Sects. 1 and 2.2, we aim for a low apparent viscosity at high compressive strength in order to reach an extrudable mixture. As expected, the finer the cement ($A_{\text{Blaine,C}} > A_{\text{Blaine,B}} > A_{\text{Blaine,A}}$), the higher is the resulting strength of the prisms (see rectangles in Fig. 1). On top, the strength development of finer cement is faster and it therefore is supposed to be more suitable for buildability. In order to compare the pastes according to their apparent viscosity, the slump flow was set to a value of 190 ± 15 mm at the beginning of the rheological measurements by adjusting the superplasticizer dosage. Assuming that lower apparent viscosity leads to enhanced pumpability [1], CEM C is suspected to be pumped more easily than CEM B and comparably to CEM A (see Fig. 1). Consequently, CEM C was chosen for the further experiments with LP.

A partially substitution of the CEM C by five limestone powders differing in chemical composition and fineness also affected the rheology and the compressive strength (see Fig. 1). LP5 is the finest LP with a surface area of $11,400 \text{ cm}^2/\text{g}$. LP 3 and LP4 are comparable in fineness and slightly finer than CEM C while LP1 and LP2 are coarser than CEM C (see Table 1). Taking into account the silica fume, the particle size range with the coarser limestone powders becomes considerably wider and thus the packing density higher. This leads to a lower particle friction and as a consequence to lower apparent viscosity. This is in line with [2], who are comparing two systems with identical solid fraction and find that the system with various size of particles will

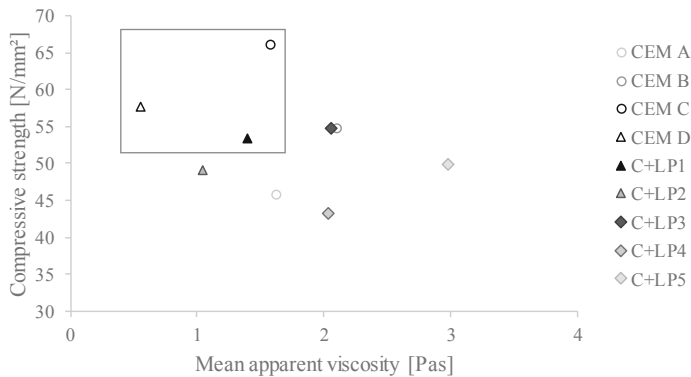


Fig. 1. Compressive strength over mean apparent viscosity of the pastes

exhibit the smaller apparent viscosity. As shown in Fig. 1, the mixtures with LP1 and LP2 have the lowest apparent viscosity of the mixtures. Furthermore, the mixture with LP1 has a higher compressive strength after 28 days. This mixture is thus suspected to have a good pumpability, buildability as well as mechanical performance (in hardened state) and was consequently chosen for the further experiments on the lightweight aggregate concrete (see Sect. 3.2).

CEM D represents the industrially manufactured cement and shows the lowest apparent viscosity and should thus be suitable for pumping (see Fig. 1). In comparison to the other mixtures it also shows a high compressive strength with 57.8 N/mm^2 . The suitability for extrusion of the three mixtures highlighted in Fig. 1 (CEM C, C+LP1 and CEM D) was further investigated with lightweight aggregate concrete in Sect. 3.2.

3.2 Concrete

Based on the results on paste, the evaluation of pumpability and buildability was conducted on concrete. Three different quantities of the selected limestone powder substituting CEM C were examined: 0 vol.% LP1 (CEM C = CEM C), 20 vol.% LP1 (C+20LP) and 40 vol.% LP1 (C+40LP). Furthermore, we compared them to the specially produced cement CEM D.

The experiments on pumpability show that the pressure and the flow rate augment with increasing pumping speed (see Fig. 2). The speed is controlled by the frequency of the drive shaft – we compared 7.3 Hz, 15.6 Hz and 26.2 Hz as described in Sect. 2.3. The correlation is valid for all mixtures. If we additionally compare the mixtures with each other, it is noticeable that there is a correlation between pumpability and LP content. The mixtures with the largest amount of LP were pumped most easily, i.e. showed the lowest pressure at constant flow rate or the highest flow rate at constant pressure, respectively (see Fig. 2). The pumpability consequently enhances with increasing amount of LP.

It has to be noted that CEM C did not yet reach a constant pressure value for the pumping speed of 7.3 Hz when it was increased to the next pumping speed level. The pressure at 7.3 Hz is therefore suspected to be higher than 3.9 bar. This matches the

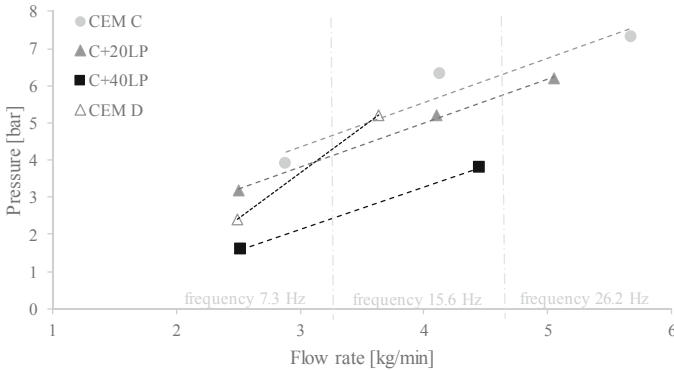


Fig. 2. Pressure over flow rate of mixtures with different amount of LP and at varying pump frequency

other values, as can be seen in Fig. 2. At lower pumping speed CEM D is pumped more easily than C+20LP as can be seen in Fig. 2. At higher pumping speed the same pressure occurred for both, but the flow rate of CEM D was lower. This might be due to different change in density as will be explained later.

Looking at Fig. 3a, we find a correlation of the pressure and the limestone content. It can be assumed that the low pressure is due to the formation of a lubrication layer. In order to compare the mixtures according to their apparent viscosity, the slump flow was set to a value of 180 ± 15 mm at the beginning of the rheological measurements by adjusting the superplasticizer dosage. We find a correlation of the pressure and the apparent viscosity for mixtures with a constant slump flow and thus constant yield stress of 304 ± 33 Pa before pumping (see Fig. 3b). The pumpability enhances with decreasing apparent viscosity. This result is in line with the findings in [4]. The effect of apparent viscosity on pumpability is probably due to its effect on the migration of particles and thus, the formation of a lubrication layer [9]. The lower the viscosity, the easier it is for large particles to move into the center of the hose and a thin layer of fine particles and water is created around it. During pumping, only the lubrication layer is sheared while the bulk material flows as plug.

In our investigations, we found no dependence of the pressure on the yield stress among the mixtures considered. However, the lightweight aggregate concrete exhibits an increase in density during the pumping process. This might be due to minor destruction of the lightweight aggregates as well as due to their absorption of water or paste under pressure. We find a correlation of the change in density with the pressure and thus, the pumping speed (see Fig. 4a). As pumping speed increases, the pressure increase, too (compare Fig. 2) which in turn leads to a compaction of the material (increase in density). Besides, there is also a correlation with the amount of LP (see Fig. 4b). The mixtures with 40 vol.% LP1 exhibit a higher increase in density although significantly lower pressures occur during the pumping process than with the other mixtures. This is due to a decrease in water retention with increasing LP content. In order to confirm this, we examined the water retention capacity in addition to the test setup in Sect. 2.3 using a filtration test. The filtrated water resulting from the equivalent

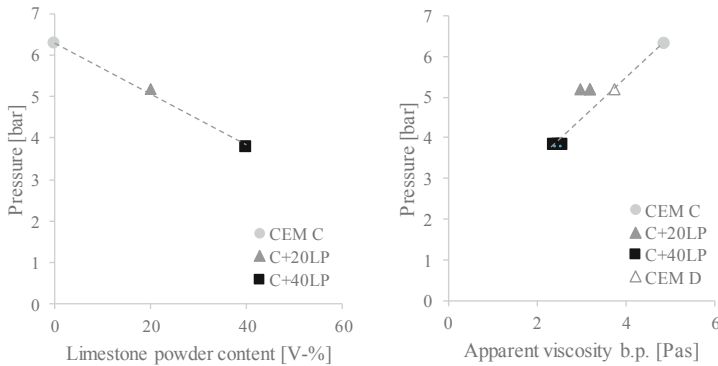


Fig. 3. Correlation of pressure and limestone content (a) as well as pressure and apparent viscosity respectively (b)

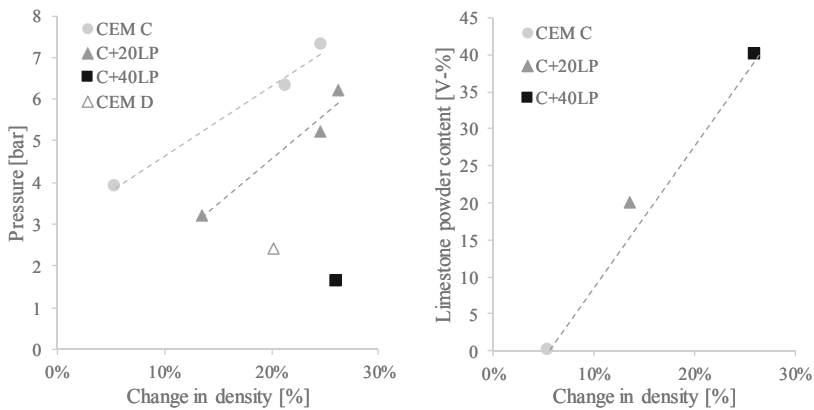


Fig. 4. Correlation of change in density and pressure (a) or limestone content respectively (b)

pastes put under a pressure load of 5 bar for 5 min was measured. CEM C showed the highest water retention, followed by C+20LP. LP 40 and CEM D had the smallest water retention.

Apart from pumpability, buildability is a major requirement for extrusion. The buildability is mainly affected by the static yield stress and the structural build-up over time [5, 6]. We find a significant increase in static yield stress of the lightweight aggregate concrete during pumping. The static yield stress after pumping is on average by 970 ± 40 Pa higher than the static yield stress before pumping (see Fig. 5).

The static yield stress was each evaluated after breaking the structure as described in Sect. 2.3. Thereafter the evaluation of structural build-up was determined after increasing rest times without another pre-shear. For the mixtures considered, we did not find a clear trend for the development of the static yield stress in dependence of the amount of limestone. This is in line with the results that no dependence between yield

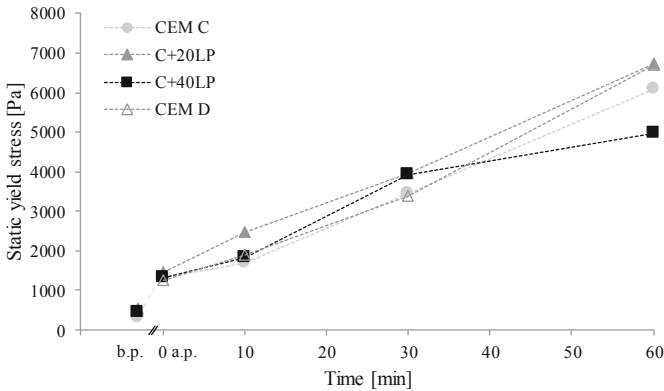


Fig. 5. Development of static yield stress during pumping and over time

stress and pressure was found. The increase in yield stress during pumping is very favorable for buildability as that means that the static yield stress at the nozzle is significantly higher than before pumping and the extruded strands can thus bear more weight and sustain their shape more easily. According to calculations based on [6] and real 3D-printing tests a yield stress of 1,000 Pa or higher in combination with a structural build-up of at least $A_{thix} = 62$ Pa/min enables to achieve a printing speed of 1 min per layer without plastic failure of the first layer of lightweight aggregate concrete.

The structural build-up of the individual mixtures is comparable within the scope of measuring accuracy: before pumping they exhibit a structural build-up of $A_{thix} = 115 \pm 5$ Pa/min. The industrially manufactured cement shows a slightly higher structural build-up with $A_{thix} = 134 \pm 11$ Pa/min. After pumping they reach $A_{thix} = 78 \pm 5$ Pa/min structural build-up in average for CEM C, C+20LP and CEM D. The structural build-up of C+40LP is slightly lower with $A_{thix} = 56$ Pa/min. This can be traced back to the lower temperature of C+40LP after pumping due to the lower cement content and thus reaction heat as well as due to the lower pressure during pumping compared to the other mixtures. At one hand the low pressure contributes to less heat development and on the other hand the significant reduction of cement leads to a slower hydration process. The difference in structural build-up before and after pumping might be due to the effect of time, as the structural build-up after mixing could be determined earlier (14 min after water addition) than after pumping (approximately 25 min after water addition, which corresponds to the beginning of the measurement at time 0 in Fig. 5). This is due to the duration of the pumping process. As described in [4] and [7], the structural build-up is higher in the first ten minutes of rest than later and it might be that some irreversible early hydration processes were destroyed in the pre-shear phase of the tests after pumping. As described above, the structural build-up of all mixtures but C+40LP is sufficient for the desired printing speed. The buildability could be further enhanced by the addition of thixotropy enhancing agents, see [4].

In terms of hardened concrete properties, the compressive and flexural strength were not reduced significantly by substitution of the cement with up to 40 vol.% limestone powder, which is among others affected by the lower drying shrinkage (see Table 2).

Table 2. Strength of mixtures with different limestone contents before pumping after 28 days.

Mixture	Flexural strength	Compressive strength	Drying shrinkage
CEM C	3.1 ± 0.3	23.3 ± 1.3	-1.29‰
C+20LP	3.0 ± 0.2	23.5 ± 0.8	-1.23‰
C+40LP	3.7 ± 0.1	24.1 ± 0.8	-1.01‰

The values of the materials before pumping can be seen as minimum values, which are increased through the pumping process due to compression. The materials pumped at 7.3 Hz have a mean value of $29.3 \pm 0.9 \text{ N/mm}^2$ compressive strength and $2.9 \pm 0.6 \text{ N/mm}^2$ flexural strength and at 15.6 Hz mean values of $33.9 \pm 1.4 \text{ N/mm}^2$ and $3.6 \pm 0.6 \text{ N/mm}^2$. Also in this case, the flexural strength does not decrease or even increases with increasing LP content. The compressive strength is not affected significantly.

4 Conclusion

In our investigations we analyzed the extrudability of LAC. We found that the pumping performance enhances with increasing LP content. At the same time the density rises during the pumping process with increasing LP content and water retention which leads to higher strength after the pumping process. Furthermore, we found that independent of the LP content, the static yield stress increases significantly during the pumping of LAC, which further facilitates the buildability in addition to the relief from the low density. This means that fast construction times can be achieved even with a lower structural build-up rate. Another advantage is that the replacement of the cement by LP leads to less drying shrinkage without reducing the strength of the components. Furthermore, the replacement of the cement reduces the energy consumption in addition to the material savings through the manufacturing process itself.

Acknowledgements. The research documented in this paper was conducted within the project ‘Additive Manufacturing of Multifunctional, Monolithic Wall Elements by Extrusion of Lightweight Concrete’. It was funded by the innovation program ‘Zukunft Bau’ of the Federal Ministry of the Interior, Building and Community, Federal Republic of Germany (project number SWD-10.08.18.7-17.14).

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Numerical Modeling of an Extrusion-Based 3D Concrete Printing Process Considering a Spatially Varying Pseudo-Density Approach

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Abstract. During the past few years, additive manufacturing techniques for concrete have gained extensive attention. In particular, the extrusion-based 3D concrete printing exhibited a rapid development. However, further progress is hampered by a time-consuming trial-and-error exploration, i.e., mainly experimental studies have been performed so far. A more fundamental understanding of the relations between the printing process, the process parameters and the properties of the printed product could be achieved by means of numerical simulations. They enable to study a wide range of parameters such that dependencies of properties of the printed product on different influencing factors can be identified. Taking into account the uncertain nature of the process and material parameters of the extrusion-based 3D concrete printing, the process can be reliably controlled and finally optimized.

The present study introduces a novel modeling approach, applying the Finite Element (FE) method while considering a pseudo-density approach. This density is used to define the material properties of each FE, similarly to the soft-killing approaches in topology optimization. Along with the progressing printing process, a previously generated FE mesh is activated layer by layer. Additionally, all material parameters vary temporarily due to the time dependency of the curing process. The numerical simulation allows to investigate the deformation behavior of the printed wall for different printing velocities.

Keywords: Extrusion-based technique · 3D concrete printing · FEM simulation · Pseudo-density approach · Strength-based failure

1 Introduction

In the past few decades 3D concrete printing technology (3DCP) is getting recognition in the construction industry. The technology has several advantages such

as decreased construction time, design flexibility compared to conventional construction methods, cost reduction by avoiding formwork costs, reduced waste, reduced manpower which decreases injuries and fatalities on construction sites and increased sustainability of the construction industry [3, 8]. A growing number of projects can be observed in both private enterprises and research institutes worldwide [2]. According to Wangler et al. [13] among the different concrete printing processes, the extrusion-based process is the most widely used. Therefore, the presented contribution considers the extrusion-based process which has been demonstrated to be applicable to the construction industry.

However, there are several challenges to be addressed to fully implement the technology. An improved profound understanding of the relationship between design, material behavior, and process parameters would be grate. Many researchers indicated that the materials' rheology and the process parameters, such as printing speed, time, temperature, etc, have an impact on the fresh and hardened state of the printed structure [7]. Due to the complex nature of material parameters and printing process parameters, adequate process parameters are commonly determined by means of a trial-and-error procedure. This makes 3DCP more expensive and time-consuming than necessary [10].

By implementing a numerical simulation of the 3DCP process the trial-and-error procedure could be avoided. In addition, a more fundamental understanding of the relations between the printing process, the process parameters and the properties of the printed product could be achieved.

This study introduces a novel modeling approach, applying the finite element (FE) method while considering a pseudo-density approach, where the elements are endowed with a spatially-varying pseudo-density, similar to the soft-killing approaches in topology optimization, proposed by Bendsoe and Sigmund [1].

Along with the progressing printing process, a previously generated FE mesh is activated layer by layer. Material parameters do change with time according to the hardening process. Furthermore, the authors in [14] experimentally obtained results that exhibits the mechanical properties of printed concrete showing visible randomness. Therefore, the material is described using spatially and temporarily varying material parameters. Applying the proposed approaches a failure mechanism that might occur during extrusion-based 3D printing processes of straight, free-standing wall structure could be reliably estimated.

2 Numerical Model of an Extrusion-Based 3D Concrete Printing

The numerical model is prepared using commercially available programming language (MATLAB) to predict the structural behavior of a straight, free-standing walls generated during a extrusion-based 3DCP process.

2.1 Finite Element Model with Pseudo-Density

The wall configuration is modeled as a two-dimensional structure and constructed in a layer-wise process. A FE mesh with 4-node bi-linear elements are

used. The defined boundary conditions a fixed bottom layer as a result of friction on the printed bed [14] and non-uniform self-weight load as a result of the layer-wise production process is activated as the printing progresses. The layer-wise production process of the concrete structure is included in the FE model while considering a pseudo-density approach. The algorithm is prepared based on the previously generated FE mesh where the elements are endowed with a spatially varying pseudo-density $\rho(x) \in [0, 1]$.

Along with the progressing printing process, the layer-wise activation of each finite element is realized by defining $\rho(x)$ such that $\rho(x) = 1$ holds for all built parts of the structure and $\rho(x) = 0$ for those not build yet. Intermediate values are considered if an element is partly “filled” by a freshly printed line, where the fresh printed line does not match with FE mesh. As an example if half of the FE is filled by the freshly printed line then $\rho(x) = 0.5$, counting solely with half the weight until the other half is filled with the next fresh printed layer. This idea inspired by the soft-killing approach in topology optimization [1] avoids time consuming remeshing for the changing geometry of the printed wall (Fig. 1).

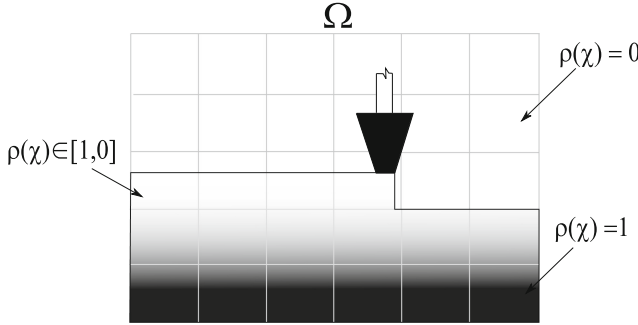


Fig. 1. Illustration of the pseudo-density approach.

These densities are used to scale the material parameters. For example the Young’s modulus of each FE is expressed as a function of $\rho(x)$ given by the modified SIMP (Simplified Isotropic Material with Penalization) interpolation scheme [12]:

$$E(x) = E_{\min} + \rho^p(x)(E - E_{\min}), \quad (1)$$

where $E(x)$ denotes the resulting stiffness of the concrete, $E_{\min} > 0$ is a lower bound to ensure positive entries in the resulting global stiffness matrix, E refers to the nominal Young’s modulus. Further, the penalization parameter p is chosen as $p > \frac{2}{1-\nu}$, where ν denotes Poisson’s ratio.

2.2 Spatial and Temporal Changes of the Material Parameters

To ensure a successful printing process and a reliable final product during the extrusion technique, several rheological properties requirements need to be fulfilled by the concrete. During the extruding the concrete should be flowable so

that it could be pumped, after deposition, it should be stiff to carry the subsequent layers. In addition, the time gap between consecutive layers should be limited to increase the bond strength between two consecutive layers [4].

At each stage (pumping, extruding and depositing) of the extrusion process, the rheological properties and the mechanical behavior of the concrete varies. For the concrete to be pumpable the yield stress and viscosity should be as low as possible [9], and to ensure the buildability of the structure, the concrete should rapidly gain strength and have an adequate yield stress [6,9]. The static yield stress evolution for the extrusion-based printing process is shown in Fig. 2. At the pumping and extruding stage the fresh concrete is represented in light grey and after deposition, the concrete is represented in dark grey. The numerical simulation includes this evolution of the yield stress due to the time dependency of the curing process. The first deposited layer has the maximum age compared to the last deposited layer. In the algorithm as each layer is activated this spatial variation is considered.

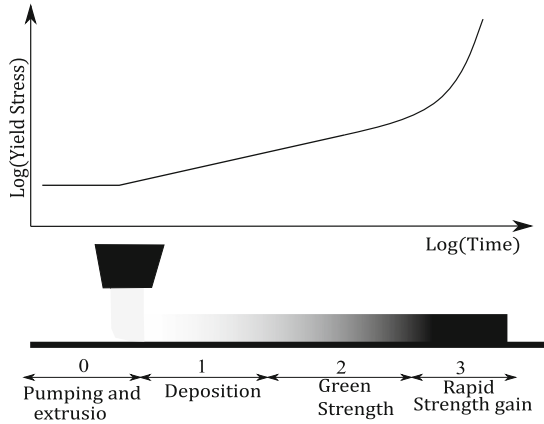


Fig. 2. Evolution of the static yield stress for the extrusion-based printing process according to [6].

Wolfs et al. [14] experimentally determined the temporal evolution of the compressive strength and Young's modulus of the curing process, and has developed equations based on the average results. The experimental results indicate that both compressive strength and Young's modulus are directly proportional to the time. Based on these findings, the numerical model accounts for temporal changes in a material parameters P in the form of

$$P(t) = P_0 + \beta_P \cdot t, \quad (2)$$

where P_0 indicates the initial material parameter value and β_P the linear increase per time t .

In the numerical model both the spatial and temporal variations of the material parameters are included in the FE system of the form

$$\mathbf{K}(\rho(x), t) \mathbf{u}(\rho(x), t) = \mathbf{F}(\rho(x), t), \quad (3)$$

where $\mathbf{F}$ is the loads due to self-weight, which also increases as an increase of the subsequent concrete layers, $\mathbf{K}$ denotes the stiffness matrix and $\mathbf{u}$ the vector of nodal displacements.

3 Results and Discussions

The geometry of the numerical simulation include wall width $w = 43.5$ mm, wall length $L = 1000$ mm, thickness of each layer $t = 10$ mm, Poisson's ratio $\nu = 0.3$ and material density $\rho = 2020$ kg/m³. The analysis was limited to a number of 17 layers to avoid the elastic buckling according to a parametric model developed by Suiker et al. [10].

3.1 Geometric Deformation

Printing with wet concrete could cause geometrical difference between the final printed structure and the CAD model, to ensure the quality of the printed object it is necessary to evaluating the consistency between the printed object and the CAD model [5]. The deformation of layer 17 and 7 are shown in Fig. 3 and Fig. 4, respectively. The results indicate geometrical variation between the expected position and the final position. It can be noted that the deviation of the final from the expected position is larger for the top layer than for the 7th layer due to additive layer-by-layer production.

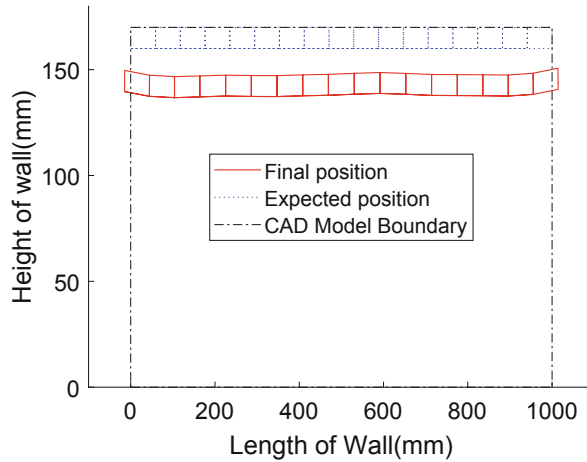


Fig. 3. Top layer of the printed wall with printing velocity of 5000 mm/min: expected and final position

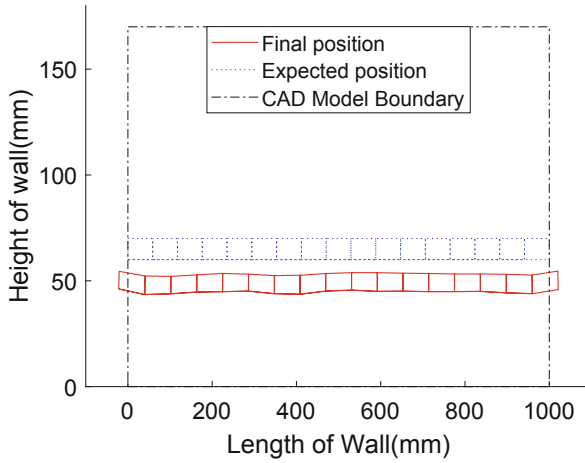


Fig. 4. Seventh layer of the printed wall with printing velocity of 5000 mm/min: expected and final position

The simulation was performed for different printing velocities v_p , since a significant influence on the surface roughness, the compressive strength, and the interlayer bond strength is expected [11]. Printing velocities between 100 mm/min to 3000 mm/min were investigated. Based on the above observation the impact on the final printed object geometry could be investigated. Keeping the number of layers constant, while ensuring no failure regarding the elastic buckling and the plastic collapse. The maximal vertical and horizontal displacement for each layer are shown in Fig. 5a and Fig. 5b for different printing velocities v_p .

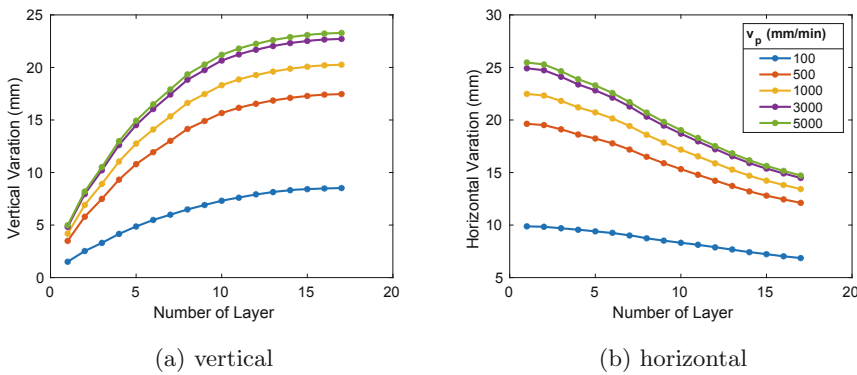


Fig. 5. Vertical and horizontal variation of each layer as a result of the varying printing velocity v_p

While the maximum vertical displacement increases at the higher layers, the maximal horizontal displacement is found at the bottom layer, which resembles the naturally expected deformation behavior. Both, maximum vertical and horizontal displacement w.r.t. the whole wall, increases with increasing printing velocity. The behavior of the maximum vertical and horizontal displacement of the wall is summarized in Fig. 6. It can clearly be seen that the maximum displacement increases for increasing printing velocities for both vertical and horizontal deflection. Additionally, the slope of the shown functions are much steeper in the regime of lower than higher printing velocities, indicating a strong influence of the time-dependent material properties.

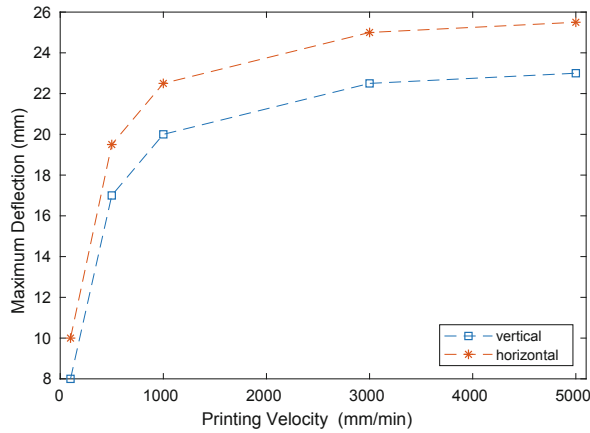


Fig. 6. Maximum vertical and horizontal displacement as a function of the printing velocity

3.2 Influence of Printing Velocity on Layer Interface Strength

Another crucial parameter of 3DCP is the layer interface strength, which depends on the waiting time between the subsequent layer as well as the thixotropy of the material. The longer the time gap between layers the higher the thixotropy, the weaker is the interface. Cold joints are expected to arise between successively printed concrete layers, if the time gap exceeds a maximum $T_{\max}$ given in [9]

$$T_{\max} = \frac{\sqrt{\frac{(\rho g h_0)^2}{12} + \left(\frac{2\mu_p v_p}{h_0}\right)^2}}{A_{\text{thix}}}, \quad (4)$$

where h_0 is the thickness of one layer, μ_p is the plastic viscosity, v_p is the printing velocity and A_{thix} is a thixotropy parameter (structuration rate), ρ the density of the printed material and g is gravitational constant. The plastic viscosity and

struction rate for printable concrete is taken from [4]. The actual time gap was calculated for each printing velocity by L/v_p , L is the length of the single layer. The result of the actual and (theoretical) maximal allowed time gap are shown in Fig. 7 for different printing velocities. To avoid the creation of cold joints the actual time gap between each layer should be less than $T_{\max}$. As it can be observed from Fig. 7, cold joints are formed for printing velocity of 100 mm/min and 500 mm/min. Consequently this printing velocity for the considered printing material is not recommended.

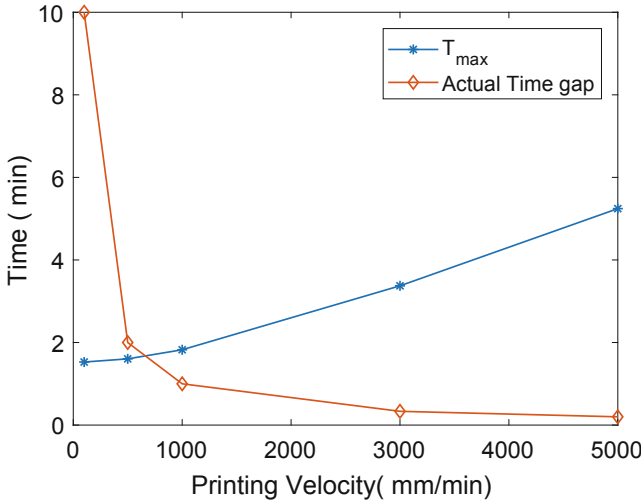


Fig. 7. The maximum allowed time gap between layers ($T_{\max}$) and the actual time gap

4 Conclusion

The numerical model captures the process of extrusion-based printing by considering the spatial and temporal variation due to the time dependency of the curing process. The geometric deformation shape of a 1 m wide wall was analyzed. On one hand, it showed significantly larger deformations for higher printing velocities than for velocities lower than 500 mm/min. On the other hand, the time gap between consecutive layers was found to be larger the maximum time gap ensuring a interface bond. Using the spatially varying pseudo-density approach a efficient numerical simulation was used, enabling to simulate the time dependent behavior of the 3DCP. The numerical model was used to investigate the process parameter printing velocity to predictive the deformation behavior and interface bond strength, rather than employing time consuming trial and error exploration.

In the future, the influence of additional material and process parameters will be studied, for example stochastic description of material and process parameters will give rise to a more realistic 3DCP model. Further studies of failure mechanism could be used to perform reliability analysis for the 3DCP.

Acknowledgment. The work has been financially supported by different institutions which is highly acknowledged. Among them are: DAAD (Ethiopian - German Exchange of PhD candidates), DFG (German Research Foundation) priority program 1886 “Polymorphic uncertainty modelling for the numerical design of structures” and the Federal State of Thuringia, Germany.

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Evaluating the Influence of Aggregate Content on Pumpability of 3D Printable Concrete

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Abstract. 3D concrete printing technology has gained huge momentum in the past two decades. The enhanced geometric freedom associated with 3D concrete printing could be beneficial for a variety of applications. However, the relatively high binder content in 3D printable concrete makes them less sustainable compared to mould-cast concrete. Therefore, developing printable mixtures with the required rheological behaviour combined with enhanced sustainability is very important. In this study, different concrete mixtures were prepared by replacing ordinary portland cement with ground granulated blast furnace slag. A polycarboxylate-ether-based superplasticizer and a cellulose-based viscosity modifying agent were used as chemical admixtures. A maximum aggregate size of 2 mm was used, and the aggregate-to-binder ratio (a/b) was varied from 1.0 to 1.8 to reduce the binder amount. The designed mixtures were tested for their pumpability with a screw-based pump system allowing to measure the discharge rate and pumping pressure. The pumping pressure increases as the aggregate content increases. Rheological properties of these mixtures were determined by fitting to the Bingham model. The yield stress and viscosity were found to increase with an increase in the aggregate content of the mixtures.

Keywords: 3D concrete printing · Slag · Sustainability · Aggregate content · Pumping

1 Introduction

Additive manufacturing or rapid prototyping is a novel method in the concrete construction field. During the last couple of decades, the applicability of additive manufacturing in the construction sector was greatly explored all around the world [1–3]. Based on the method of material deposition, additive manufacturing can be classified into different types such as D-Shape, contour crafting and the 3D concrete printing (3DCP) [3]. Among these methods, 3DCP has proven as a viable way of constructing elements ranging from laboratory scale specimens to

big houses [3]. In 3DCP, the cementitious mixture gets deposited in a layer-by-layer manner based on a computer model. In the 3DCP process, the fresh mixture has to undergo various flow conditions during pumping and then the extrusion process [4]. During pumping, the mixture should be fluid enough to achieve a constant discharge rate with reasonable pumping pressure. Then, as soon as the material exits the nozzle and gets deposited as a filament layer, it should achieve enough shear strength to resist the shear stress due to its self-weight (shape stability) and the weight of the subsequent layers (buildability). These two parameters mainly depend on the yield stress of the cementitious mixture [4]. Several researchers have developed printable mixtures based on the yield stress criteria and reported that the yield stress of printable mixtures could be in the range of 1 to 3 kPa [2, 5]. However, the mixtures with high yield stress are relatively difficult to pump as the pumping pressure can be proportional to the fourth power of the yield stress as per Buckingham-Reiner equation [6]. Also, during the printing process, the failure of layers can happen due to buckling. Such a failure would depend upon the elastic modulus, and its evolution with time [4, 7].

To meet the rheological requirements for pumpability and buildability, most often, 3D printable concrete mixtures are designed with more binder content than the conventional mould-cast concrete. Figure 1 shows some of the printable mixtures reported in the literature. It can be seen that all printable mixtures have binder contents higher than about 800 kg/m³. When compared with a typical self-compacting concrete mixture with a binder content of 400 kg/m³, it is clear that the printable mixtures contain a high amount of binder (about 50% higher). As the binder mainly consists of portland cement, such mixtures have a high carbon foot-print. Therefore, it is evident that the printable cementitious mixtures are less sustainable compared to conventional mould-cast concrete. One of the ways to make printable concrete more sustainable is by increasing the aggregate content. For this, the effect of aggregate content on the pumpability needs to be understood.

In the current study, high yield stress concrete mixture compositions with different aggregate-to-binder ratio (a/b) are developed using the flow table test. The effect of a/b on the yield stress and plastic viscosity is studied by performing rheological experiments using a dynamic shear rheometer. Pressures required to pump these different mixtures are also determined by performing pumping studies using a constant displacement screw-based pump system. Finally, the experimental values are compared with the discharge rate predictions obtained using the Buckingham-Reiner equation [6].

2 Materials and Methods

Ordinary portland cement (CEM I 52.5 N) conforming to EN 197-1 [13] and ground granulated blast furnace slag (GGBS) were the main binders used in this study. The specific gravities of the binders were 3.19 and 2.89 respectively. The oxide compositions and physical properties are given in Table 1. A

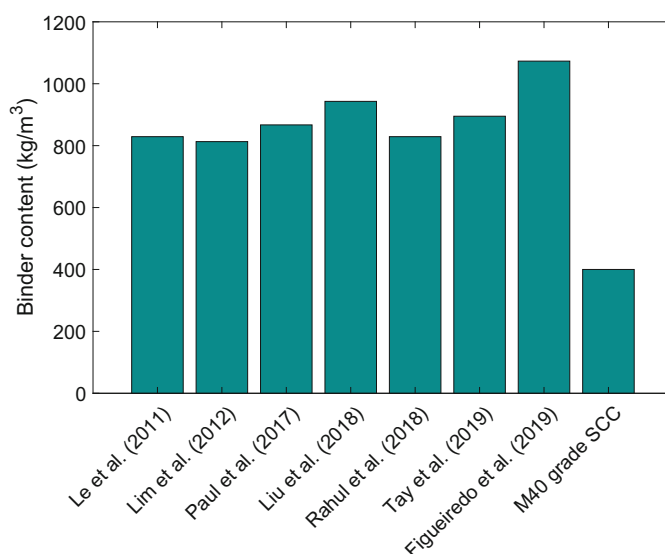


Fig. 1. Overview of printable mixtures reported in literature [2,5,8–12]

Table 1. Chemical composition and physical properties of the binders

Material	Quantity (% by mass)	
	OPC	GGBS
CaO	64.30	37.97
SiO ₂	18.30	35.60
Al ₂ O ₃	5.20	13.12
Fe ₂ O ₃	4.00	0.37
(Na ₂ O) _e	0.32	0.74
MgO	1.40	7.24
SO ₃	3.50	7.24
LOI	1.40	0.95
Blaine area (m ² /kg)	408	428
Density (kg/m ³)	3190	2890

polycarboxylate-ether-based superplasticizer and cellulose-based viscosity modifying agent (VMA) were used. Aggregates consisted of river sand having 2 mm nominal size and specific gravity of 2.65.

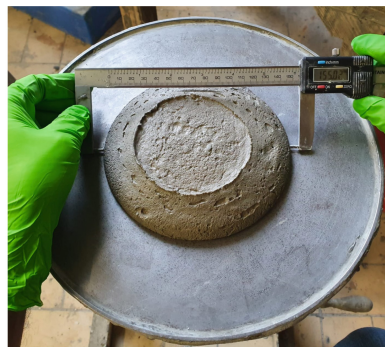
The mixing was carried out with a planetary mixer. Each time, about 15 L of mortar was prepared. The mixing process involves the dry mixing of all the ingredients for 30 s and then adding the superplasticizer mixed beforehand with the water. After the addition of superplasticizer, the mixing was continued for

3 min. Then, the VMA was added to the mixture and mixing was continued for 2 more minutes.

The mixture design of the printable mixtures was carried out by using the flow table test, in accordance with ASTM C1437-2015 [14]. Figure 2 shows the flow table apparatus and a typical flow spread diameter measurement. The rheological studies were carried out using MCR 102 rheometer. A six-blade vane and cylinder with roughened surface were used. The test protocol consisted of a pre-shear of 10 s^{-1} for 60 s, followed by a step ramp-up and ramp-down of strain rate as shown in Fig. 3. The steady state stress response obtained from the ramp-down portion was fitted with the Bingham model to obtain the yield stress and plastic viscosity of the different mixtures. The pumpability was evaluated by pumping the mixtures using a screw pump. The material was pumped out through a 5 m long and 30 mm diameter rubber pipe until the discharge rate was uniform and constant. Then the pumping pressure was monitored using the pressure sensor attached at the inlet of the pipe. All the experiments were carried out twice and the average values were reported.



(a) Flow table apparatus



(b) Spread diameter for mixture 1

Fig. 2. Flow table test (ASTM C1437-2015 [14])

3 Results and Discussions

Initially, a control mixture (mixture 1) was developed with a/b of 1.0. For this, the superplasticizer dosage was varied until the mixture exhibited very low deformation during printing. The average flow spread diameter of mixture 1 was observed as 154 mm. Liu et al. (2019) [10] suggested that there exists a printability region based on the flow spread diameter for the printable mixtures. The authors reported that when the flow spread values are within a specific range, the mixture would be printable. A flow spread diameter of 150–160 mm was identified as the printability region for this study. By changing the superplasticizer dosage, subsequent mixtures with higher aggregate content (mixtures 2

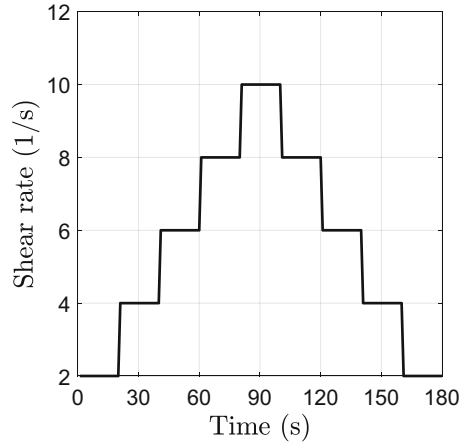


Fig. 3. Protocol for ramp-up and ramp-down test

and 3) were also designed to have a flow spread within this printability region. For all the mixtures, VMA was used at a nominal dosage of 0.1 % of the binder content. The optimized superplasticizer dosages and flow table test results are summarized in Table 2. It is clear that as the aggregate content increases, more superplasticizer is required to maintain the mixtures in the printability region. This can be due to the reduced water content in mixtures 2 and 3 as compared to the same volume of mixture 1.

Table 2. Average spread diameters of the mixtures from flow table tests

Mixture name	a/b	Superplasticizer (% of binder)	Average spread diameter (mm)
1	1.0	0.04	154
2	1.4	0.10	160
3	1.8	0.20	159

Figure 4 shows the flow curves and the Bingham fits of all three mixtures. From the model fit, the yield stress of the mixtures was determined by extrapolating the flow curve to the y-axis. Figures 5a and 5b show the yield stress and plastic viscosity of the three mixtures. The values reported in figure are the average values and the error bar indicates the standard deviation from the average values. It can be seen that mixture 3 has 20% more yield stress and about 150% more viscosity than mixture 1. Though the mixtures were designed for a similar flow value (consistency), the viscosity can be drastically different. Hu and Wang [15] and Geiker et al. [16] also reported a similar trend. As the aggregate content increases, the paste volume decreases in the mixture. This can result in enhanced

inter-particle friction between the aggregate particles as there will be less paste available to coat the aggregate surfaces [15]. Figure 6 shows the variation of the pumping pressure as the aggregate content increases. From Fig. 6, it is clear that the pumping pressure increases with an increase in aggregate content for a constant discharge rate. The discharge rate for a Bingham fluid can be evaluated by Buckingham-Reiner equation [6] as given below

$$Q = \frac{\pi(3R^4 \Delta p_{tot}^4 + 16\tau_0^4 L^4 - 8\tau_0 L R^3 \Delta p_{tot}^3)}{24\Delta p_{tot}^3 L \mu_p}, \quad (1)$$

where Q is the discharge rate in m^3/s , R is the pipe radius (m), L is the length of the pipe, τ_0 is the yield stress (Pa), μ_p is the plastic viscosity (Pa·s), and Δp_{tot} (Pa) is the pressure loss over the length, L .

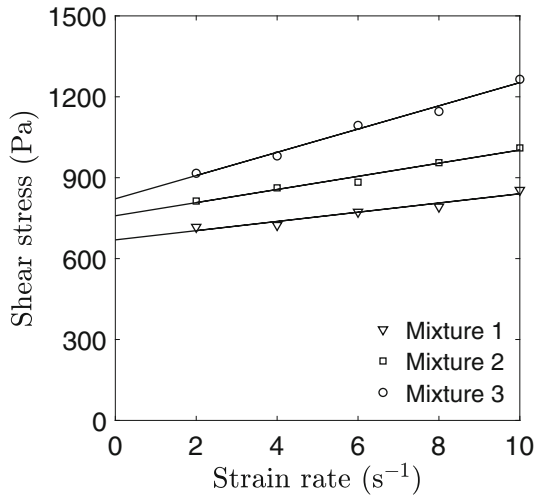


Fig. 4. Flow curve with Bingham fit

From Eq. (1), it can be seen that the discharge rate of the fluid depends on the material properties as well as the pipe dimensions. From the pumping experiments, pumping pressure needed for a constant discharge rate of 300 ml/s was measured for all mixtures. Also, using Eq. (1), discharge rate was predicted for all the mixtures. The comparison is shown in Table 3. The predicted discharge rate is significantly lower than the experimental observed values for all the mixtures. This significant difference could be due to the fact that the pipe flow of a heterogeneous material like concrete is different from the flow of a typical Bingham fluid. During the pumping of concrete, a paste rich lubricating layer forms at the concrete-pipe wall interface, which is not accounted for in the Buckingham-Reiner equation [6]. Moreover, the use of more accurate pressure sensors can give accurate discharge rate values during the experiments. The differences between the measured and predicted discharge rates could be due to these factors.

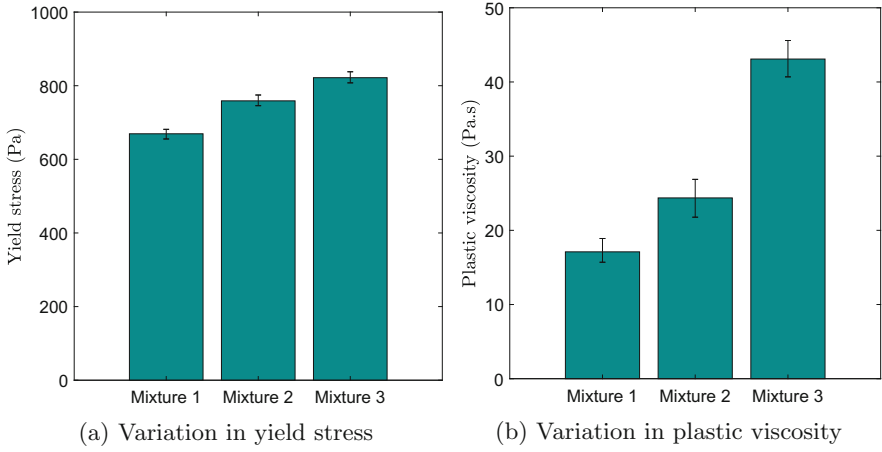


Fig. 5. Variation in the rheological parameters with increasing aggregate content

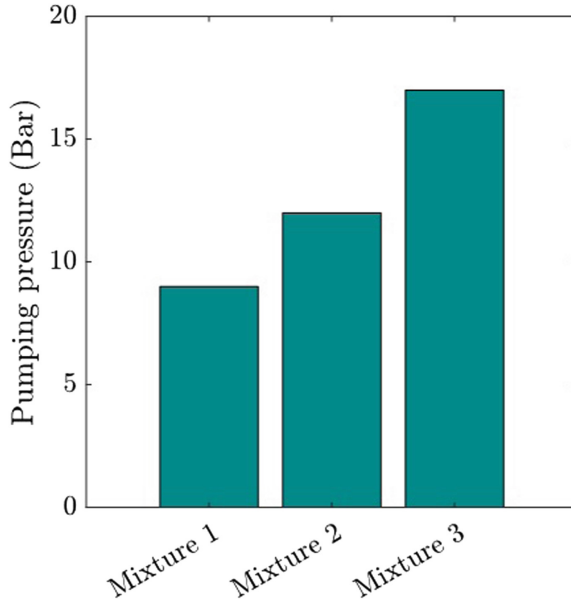


Fig. 6. Variation of pumping pressure of the mixtures at a constant discharge rate of 300 ml/s

4 Summary and Conclusions

The current study gives an insight on the effect of aggregate content on the pumpability of high yield stress fluids such as printable concrete. The study starts from a mixture design and then, systematically evaluates the pumpability

Table 3. Predicted and measured discharge rates from the pumpability studies predicted and measured discharge rates from the pumpability studies

Mixture	Predicted discharge rate (ml/s)	Yield stress (Pa)	Viscosity (Pa.s)
1	75.1	669	17.1
2	87.6	759	24.4
3	89.9	822	43.1

with increasing aggregate content. The following conclusions can be drawn from the current study:

- As the aggregate content increases, the yield stress and viscosity increases. This could be because of the increase in inter-particle friction between the aggregates. Further, the increase in the viscosity is more prominent than the increase in yield stress.
- As the aggregate content increases in the mixture, pumping pressure also increases. This may be due to the higher yield stress and plastic viscosity of the mixtures with higher aggregate content. The discharge rate predictions using Buckingham-Riener equation do not match well with the actual discharge rate observed from the pumping experiments. This could be due to the lubrication layer formed at the concrete-pipe wall interface, which is not considered in the Buckingham-Riener equation. Further studies characterising the properties of lubrication layer are needed to make more reliable pumping pressure predictions.

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2D Numerical Modelling of Particle-Bed 3D Printing by Selective Paste Intrusion

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Abstract. Additive manufacturing of concrete and cement based materials is expected to revolutionize how structures are built. 3D printing processes by means of extrusion-deposition have recently been developed at the scale of few meters for houses or structural elements but not yet for several floors. Among the 3D printing processes which have also gained attention, particle-bed methods could be designated as an innovative one. In the case of the selective paste intrusion technique, the nozzle of the 3D printer applies the binder composed of water, mineral material and admixtures to a particle bed of sand particles. To reach a homogeneous material using the selective paste intrusion method, the aggregate layer made of sand must be completely penetrated by the cement paste to bond with the other layers. Such an issue is challenging regarding the rheological requirements of the binder to ensure the complete penetration of the aggregates layer. Therefore, this paper aims to provide and validate the penetration of yield stress fluids through sand particle layers using numerical simulation. A 2D numerical analysis is carried out to study the preferential flow path comparing to previous unidirectional modeling. A level-set method and a continuous viscoplastic model have been used to simulate the penetration and to compare the numerical results with experimental and analytical models from the literature. We describe the penetration as a function of the yield stress, the contact angle at the interface, the medium diameter of the sand particles, the void fraction of the sand packing and the dimension of the sand layer. We show that the numerical modelling is able to predict the evaluation of penetration depth as a function of the yield stress of the fluid measured from rheological measurements and the sand particles bed properties.

Keywords: 3D printing · Particle bed method · Selective paste intrusion

1 Introduction

Barak Obama, former president of United States; said in 2013 that 3D printing has the power to revolutionize the way we made almost everything. Even that 3D printing processes are known from the early 1980, digital construction projects have risen over the last five years and a digital revolution has started to shape concrete [1]. However, scientific challenges have emerged in the use of 3D printing techniques [2, 3].

3D printing with cement based materials has already been the subject of several studies for contour crafting or extrusion/deposition processes [3]. Another promising way is to use particle-bed 3D printing [3, 4]. This additive manufacturing technique for automatically production of free-form structures is based on two repetitive steps: application of a layer of dry mineral particles followed by a selective deposition of a liquid binder or activator onto the particles in order to locally bound the particles [4]. The unbound particles are then removed to establish the final form.

This paper aims to provide and validate numerical simulations reproducing the penetration of two cement based suspensions or yield stress fluids based on its rheological properties such as viscosity, yield stress of Bingham model through three different sand packings. We will focus on the influence of the rheological properties (yield stress and viscosity) on the final penetration depth as these are the key parameter governing the stop of the flow [5]. The numerical methodology proposed here aims to solve two-phase flows using finite element code with a level-set method. We compare the numerical modelling results with the analytical modelling results from Pierre et al. [6]. Finally, the comparison between both numerical simulations and analytical model highlights that the prediction of the penetration depends on the sand packing properties and the cement paste yield stress. We then discuss about the influence of the thixotropic behaviour and the shearing flow of the fluid all along the penetration process regarding the shear rates and the shear stress of the fluid.

2 Numerical Modelling of the Process

2.1 Modelling of the Rheological Behavior

The modelling of the behaviour of the cement paste is carried out with a regularized continuous visco-plastic model of Papanastasiou [7]. Considering the Papanastasiou model, an exponential stress-growth term is proposed to render the original Bingham model as a one with high viscosity in the limit of low shear rates followed by a continuous transition to a viscous liquid. From the review of Mitsoulis [8] and the study of Frigaard and Nouar [9], it was shown that the continuous regularized Papanastasiou model provided a reliable approximation to the ideal Herschel-Bulkley or Bingham model. According to Papanastasiou model, the dynamic viscosity of the penetrating fluid can be evaluated following Eq. (1):

$$\eta_{paste} = \eta_{exp} |\dot{\gamma}|^{n_{exp}-1} + \frac{\tau_{0,exp}}{|\dot{\gamma}|} [1 - e^{(-m|\dot{\gamma}|)}] \quad (1)$$

The exponent n_{exp} is taken to 1 as the fluid behaves as a Bingham fluid as supported by the rheological measurements carried out by Pierre et al. [6]. Values of experimental yield stress and viscosity measured from the rheological test were carried out in a previous work of Pierre et al. [6] and are used in this study.

2.2 Level-Set Method

The numerical simulations were carried out using the commercial software Comsol® and the level-set method [10, 11] to study the flow of two cement pastes through three different sand packings (medium diameters: $d_{\text{agg}} = 2.6$ mm; $d_{\text{agg}} = 1.6$ mm; $d_{\text{agg}} = 1.0$ mm). The cement pastes were characterized by rheological measurements in the work of Pierre et al. [6] (yield stresses of 2 Pa and 4 Pa; viscosity of 0.1 Pa.s).

The level-set method allows the interface tracking and a weighting technique makes available the use of a unique equation over the whole domain with an equivalent physical property function of the spatial existence phase (cement paste or air). The level set model adds the following transport equation (Eq. (2)) governing a level set function ϕ in a conservative form:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = \gamma \nabla \cdot (\varepsilon \nabla \phi - \phi(1 - \phi) \frac{\nabla \phi}{|\nabla \phi|}) \quad (2)$$

With ε the parameter determining the thickness of the interface; γ is initialization parameter (set to 1), and $\mathbf{u}$ is the fluid velocity (m/s). The value of the parameter controlling the interface thickness is defined as the half of the maximum mesh element size in the region through which the air/paste interface passes.

Solving this equation with a refined mesh to avoid instabilities allows following the shape of the level set function stabilized across the interface. Equation (2) can be separated into two equations: Eq. (3) as a conservation law and Eq. (4) as a re-initialization equation) which are solved:

$$\frac{\partial \phi}{\partial t} + \mathbf{u} \cdot \nabla \phi = 0 \quad (3)$$

$$\frac{\partial \phi}{\partial t} = \gamma \nabla \cdot (\varepsilon \nabla \phi - \phi(1 - \phi) \frac{\nabla \phi}{|\nabla \phi|}) \quad (4)$$

The level-set method finally solves: a transport equation (Eq. 4), a continuity equation (Eq. 5) and a Navier-Stokes equations (Eq. 6),

$$\nabla \cdot \mathbf{u} = 0 \quad (5)$$

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right) = -\nabla P + \nabla \cdot (\eta (\nabla \mathbf{u} + (\nabla \mathbf{u})^T)) + \rho \mathbf{g} + \mathbf{F} \quad (6)$$

The density and the dynamic viscosity were computed using the following equations:

$$\rho = \rho_{air} + (\rho_{paste} - \rho_{air})\phi \quad (7)$$

$$\eta = \eta_{air} + (\eta_{paste} - \eta_{air})\phi \quad (8)$$

Then, the interface between the penetrating fluid and the air from the void ratio of the different sand packings can be followed as a function of time.

3 Results

3.1 Penetration Depth

Figure 1 and Fig. 2 show the penetration depth as a function of time for medium diameters of the sand bed particles and complex fluid presenting yield stresses of 2 Pa and 4 Pa respectively. The viscosities of both fluids are fixed to 0.1 Pa.s. Results from Fig. 1 show that the penetration of the fluid of yield stress of 2 Pa is complete for medium diameters of sand bed particles of 1.6 mm and 2.6 mm. The kinetic of the penetration is slower for the fluid penetrating into the sand bed of $d_{agg} = 1.6$ mm than then sand bed of $d_{agg} = 2.6$ mm. On the other hand, the penetration through the sand bed having an average diameter of 1 mm is not complete and tends to a plateau value of 6.5 mm for 10 s of penetration.

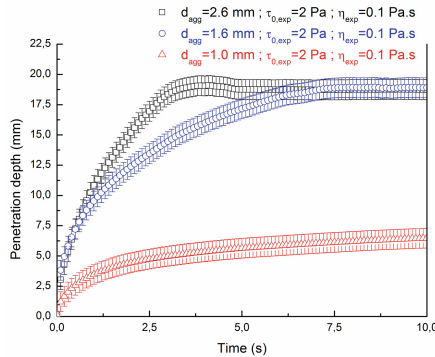


Fig. 1. Influence of the average diameter of the sand bed particles on the penetration depth of a cement paste with a yield stress of 2 Pa as a function of time.

These results clearly show that a balance between the medium diameter of the sand particles and the rheological properties of the cement paste is crucial to achieve a complete penetration during additive manufacturing method as experimentally observed by Pierre et al. [6].

As observed previously for a yield stress of 2 Pa, Fig. 2 shows that the penetration of the fluid characterized by a yield stress of 4 Pa depends on the medium diameter of the sand particles. It can be noted that the fluid with a yield stress of 4 Pa does not reach a complete penetration of the sand bed of 1.6 and 1 mm.

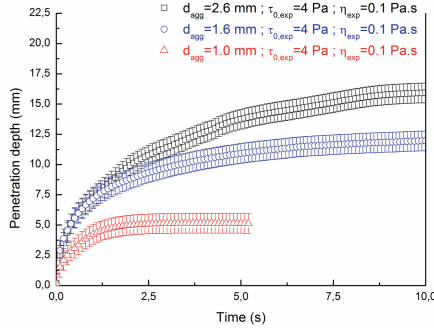


Fig. 2. Influence of the average diameter of the sand bed particles on the penetration depth of a cement paste with a yield stress of 4 Pa as a function of time.

3.2 Comparison of Experimental Results and Numerical Simulations

Figure 3 and Fig. 4 compare the penetration depth through sand particles bed of different medium diameters following numerical simulations, the analytical model and experimental measurements from Pierre et al. [6]. The experimental measurements allowed evaluating the yield stresses of the pastes from Vane Test measurements. The experimental penetration depths of the cement pastes are presented in Pierre et al. [6]. The analytical model from Pierre et al. [6] allows evaluating the height of penetration in function of paste rheological parameters and particles bed morphology following Eq. (9)

$$h_{pen} = \frac{\rho g d_{agg}(1 - \Phi_s)h_{lay}}{\alpha \tau_{0,exp} - \rho g d_{agg} \Phi_s + \frac{\Phi_s}{1 - \Phi_s} 6 \tau_{0,exp} \kappa} \quad (9)$$

Where ρ is the density of the fluid, g is the gravity, d_{agg} is the medium diameter of the sand bed particles, h_{lay} is the height of the layer of the sand packing bed, Φ_s is the sand volume fraction, $\tau_{0,exp}$ is the yield stress, κ is a parameter that represents the fraction of the sand particles surface area where the fluid is sheared. The coefficient α is a fitting parameter computed from experiments on Carbopol gels and is independent on the fluid properties. Chevalier et al. [12] propose $\alpha = 5.5$ for a spherical particle assembly. The reader can refer to the work of Pierre et al. [6] for more details on Eq. (9). Figure 3 shows that the numerical simulations results are reliable with the experimental measurements for a fluid of 2 Pa yield stress penetrating through the wet sand of medium diameters of 1.6 and 2.6 mm. A gap between the numerical value of penetration and the experimental values of penetration is noticed for the sand packing of 1 mm medium diameter. At this low medium diameter, experimental results evaluate penetration higher than the numerical model which evaluates values close to 6 mm. Several reasons, still unstudied at this stage, could explain this difference: wettability of the particles, surface tension effect, roughness and specific surface area of the sand, etc.

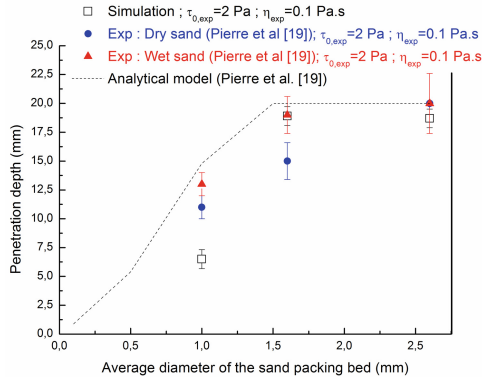


Fig. 3. Comparison of the numerical penetration depth of cement paste with a yield stress of 2 Pa and the experimental results and analytical model from Pierre et al. [6].

It can be noted that the results from numerical simulations and analytical model are also reliable for the penetration of cement paste with a yield stress of 4 Pa. It is shown in Fig. 4 that the values from experimental measurements and numerical simulations are almost similar. Then, we conclude that the agreement between numerical simulations from Finite element code and experimental results on two different cement pastes passing through three different sand packings are reliable.

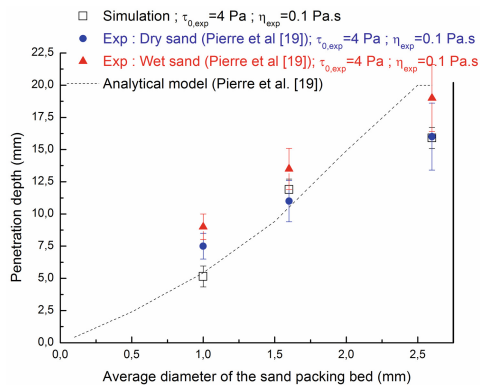


Fig. 4. Comparison of the numerical penetration depth of cement paste with a yield stress of 4 Pa and the experimental results and analytical model from Pierre et al. [6].

3.3 Influence of the Thixotropy on the Penetration Depth

As the additive manufacturing of concrete and cement based materials deals with thixotropic behaviour, the build-up of the material during the penetration is studied in this part. Please note that the increase in yield stress can be commonly considered to be

linear during the dormant period to setting [13] or exponential [14]. The consideration of the thixotropic effect follows Eq. (10):

$$\eta_{paste \quad thix} = \eta_{exp} |\dot{\gamma}|^{n_{exp}-1} + \frac{\tau_{0,exp} + A_{thix} t}{|\dot{\gamma}|} \left[1 - e^{(-m|\dot{\gamma}|)} \right] \quad (10)$$

Where A_{thix} is the structuration rate of the material which is due to flocculation due to colloidal interactions and CSH nucleation at the contact point [15]. Please note that Eq. (10) correspond to a material in which the viscosity tends to infinity as time goes on as detailed by Roussel et al. [16].

We first focus on the evolution of the shear stress as a function of the shear rate of a thixotropic ($A_{thix} = 0.5 \text{ Pa.s}^{-1}$) and a non-thixotropic fluid both with same yield stress (2 Pa) and viscosity (0.1 Pa.s) which penetrate through a sand packing of $d_{agg} = 2.6 \text{ mm}$. Figure 5 shows the shear rate and the shear stress for both fluids during the penetration. Please note that the shear stress is computed here in the porous network of the particular bed as $\tau = \eta_{paste} \dot{\gamma}$ where η_{paste} is expressed from Eq. (1) (or Eq. (10) for the thixotropic fluid) and the shear rate is expressed in cylindrical coordinates as a function of the velocity u (r component) and w (z component) following:

$$\dot{\gamma} = \sqrt{\frac{1}{2} \left(\left(2 \frac{\partial u}{\partial r} \right)^2 + \left(2 \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} \right)^2 + \left(2 \frac{\partial w}{\partial z} \right)^2 + 4 \left(\frac{u}{r} \right)^2 \right)} \quad (11)$$

Firstly, it can be observed that both fluids show a decrease of the shear stress as a function of the decrease of the shear rates. Then, we observe that at low shear rates, the shear stress tends to increase as a function of the decrease of the shear rate for the thixotropic fluid, which is usually noticed for thixotropic fluids like cement based suspensions. At lower shear rate than 12 s^{-1} , the material began to build-up and we observe the increase of the shear stress for the thixotropic fluid.

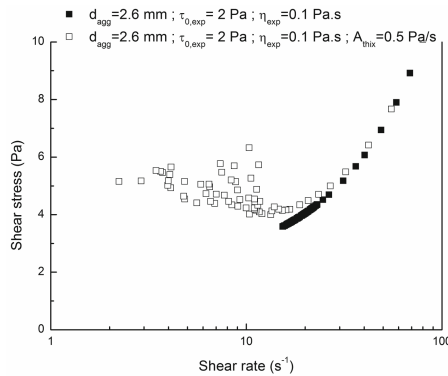


Fig. 5. Shear stress vs. shear rate during the penetration paste : influence of the thixotropy.

3.4 Shearing Behavior During the Penetration

This section is dedicated to the comparison of the shearing of the cement paste fluids during the additive manufacturing process with the selective paste intrusion method. We plot in Fig. 6 the shear stress and shear rates of the fluid computed from the numerical simulations during their penetration through the sand packing beds. Please note that we assume in this part that there is no plug flow and that the material is homogeneously sheared through the void fraction of the sand packing. It can be noticed that the shear rates range depends on the medium diameter of the sand packing bed. We observe from the numerical modeling the minima values of shear rate also decrease as a function of the decrease of the medium diameter of the sand particles bed.

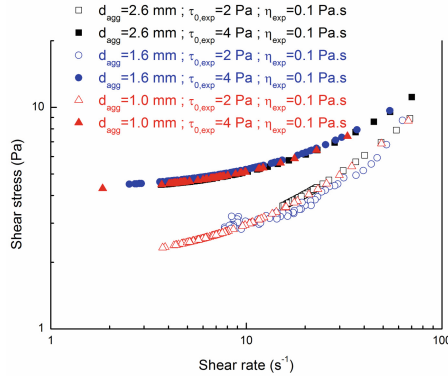


Fig. 6. Shear stress vs. shear rate during the penetration of cement pastes through three sand packing beds ($d_{agg} = 2.6$ mm; $d_{agg} = 1.6$ mm; $d_{agg} = 1.0$ mm).

In order to confirm these results, we assume that the penetrating fluid follow common Darcy law as the velocity magnitude can be express as:

$$v = \nabla P \frac{K_c}{\eta_{exp}} \quad (12)$$

Where the pressure gradient $\nabla P = \Phi_p \rho g$ with Φ_p the porosity of the sand packing taken as 0.46 and K_c is the Kozeny-Carman constant $K_c = \frac{\Phi_p^3}{45(1-\Phi_p)^2} \left(\frac{d_{agg}}{2} \right)^2$. Also, it is possible to evaluate an approximate time for the penetrating fluid through a particle bed layer height which is defined as the porous media:

$$t = \frac{\Phi_p \Delta h}{\nabla P} \frac{\eta_{exp}}{K_c} \quad (13)$$

And an average shear rates can also be computed as:

$$\dot{\gamma} = \frac{6.6}{d_{agg}} \nabla P \frac{K_c}{\eta} \quad (14)$$

According to Chevalier [12] the parameter $\frac{6.6}{d_{agg}}$ is an equivalent pipe that will represent the porous medium according to Darcy's law for a Newtonian fluid. This parameter take into account three effects: a medium width of the path between the particle much smaller than the average grain diameter; (ii) a passing section for the fluid smaller than the apparent section because of the presence of the particles (which increases the effective speed through the equivalent conduct); (iii) the tortuosity of the paths where the fluid go through and this effect tends to increase the length of these paths [12]. Then, we can compute an analytical characteristic time and average shear rates for the penetrating fluid as a function of the average diameter of the sand particles bed (Table 1).

Table 1. Theoretical average velocity, average time and average shear rate for the penetration of Newtonian fluid through sand packing bed depending on the medium diameter of the sand.

d_{agg} mm	Velocity $m.s^{-1}$	Time s	Shear rate s^{-1}
2.6	$4.53 \cdot 10^{-3}$	2.03	11.31
1.6	$1.71 \cdot 10^{-3}$	5.37	6.96
1	$6.69 \cdot 10^{-3}$	13.74	4.35

From the values of Table 1, we also observe that the average shear rate decrease with decreasing values of the median diameter. Also, it can be noticed that the time for an entire penetration of the sand particles bed increases as a function of the decreasing average diameter. Also, as the flocculation time of cement at rest due to colloidal interaction is about a couple of seconds as reported by Roussel [15], it could be interesting to focus on the experimental measurement of the velocity during the penetration using innovative techniques like tomography. A competition between the critical shear rate of the penetration and the structuration rate of the cement based or concrete suspension should be discussed in further studies about the potential stop of the flow during the penetration.

4 Conclusion

The numerical simulations results were validated with analytical modeling results taking into account the sand particles bed properties and the rheology of the fluid. It has been shown that the penetration depth can be predicted using numerical simulations with the knowledge of the rheological properties of the fluid in terms of yield stress, viscosity and flow index and the particles average diameter and void solid volume fraction of the sand layer. We have shown that the printability of a component with a

selective paste intrusion method can be predicted if the yield stress and the medium diameter and the void volume fraction of the sand are known.

We moreover discussed the influence of the thixotropic effect on the penetration kinetic and the shearing of the fluid during its intrusion through the sand layer. We highlight that such thixotropic effect should be taken into account while dealing with selective paste intrusion of cement paste. Also, the evaluation of an average shear rate based on the common Darcy' law suggest that this thixotropic effect could govern the final depth as the time of flow depends on the sand particles average diameters. As a final word, it can be noted that the influence of the thixotropic effects in a further analytical model and the measurements of the flow rate trough sand packing used tomography could be challenging to improve the selective paste intrusion process.

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Effect of Vibration on the Rheology of Concrete for 3D Printing

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Abstract. A primary challenge in concrete 3D printing is the need for low yield stress for good flow through the printer and high yield stress for sustaining the self-weight and the weight of subsequent layers. The current 3D printable concrete mixture designs make limited use of aggregates. Aggregates could significantly increase the yield stress of concrete mixtures but are not used since they impede the flow of concrete through a nozzle. A novel idea is presented in this work where vibration is used to control the rheology of concrete. By including coarse aggregate, a high yield stress concrete mixture can be obtained which when vibrated loses its yield stress instantly. Granular suspensions like concrete recover their yield stress immediately after the vibration ceases. The effect of vibration on the yield stress of concrete with varying aggregate content and packing fraction is also described. It is shown that the yield stress of concrete is significantly greater than that of cement mortar and paste and this high yield stress is lost when the concrete is vibrated.

Keywords: Vibration · Rheology · Yield stress

1 Introduction

Construction with concrete without traditional formwork, by depositing concrete layer - by- layer, using automation is commonly called as “Concrete 3D printing” or “digital manufacturing” or “automated construction” [1]. This promises several benefits like decreased construction time and costs. The common methods used to deposit concrete is through extrusion or injection of concrete into layers on a 2-dimensional plane that is further stacked on top of each other [2, 3].

The concrete used for 3D printing needs to have two opposing properties. It needs to have a low yield strength to flow easily for good extrusion. But once extruded, the concrete needs to have a high enough yield strength to sustain its self-weight initially and the weight of the subsequently printed layers on top of it [1]. To make the mix extrudable various strategies are employed by different research groups around the world. Limiting the aggregate size, using high cement content, using chemical admixtures are some of the common methods used [4, 5]. On the other hand, to

increase the green strength of the concrete post extrusion, admixtures such as accelerators and viscosity modifiers are used [6, 7]. Increasing the duration between the placement of successive layers to allow the concrete to gain yield strength is also a commonly used strategy [8].

The current concrete 3D printing mixtures with high cement content and low or no aggregate content have a few potential drawbacks. These mixes not only have a low yield strength and cost more, but they are also prone to shrinkage and durability issues. By using coarse aggregate in 3D printable concrete, these issues can be addressed. Aggregates provide volume stability and are a low-cost filler material. They also significantly increase the yield strength of the mixtures. While there are certain benefits by using coarse aggregates, mixtures will have reduced extrudability due to the higher yield stress required to move it. Inspired by how stiff concrete is handled in the field, this work explores the use of vibration to make the mixtures workable.

It has been found that concrete behaves like a Newtonian fluid during vibration at low shear rates and can flow under its own weight [9–13]. These works have also reported the response of concrete to vibration as immediate and reversible. Juradin and Krstulovic showed that vibration does not affect cement paste and reduces friction in particles greater than 0.25 mm only [11]. Their work describes the formation of a fluid phase around aggregates which reduces friction. Yield stress in concrete arises from the contact between aggregates. During vibration, the fluid phase around the aggregates acts to reduce this contact between aggregates and reduces the yield stress of concrete. Hanotin et al. have shown that the yield stress of granular suspensions is dependent on the solid volume fraction and the packing fraction [14].

The various advantages of including coarse aggregate in 3D printable concrete such as lower cement content, shrinkage resistance, lower cost, and mainly increased yield strength are the motivation behind this work. Using vibration to control the rheology of concrete is explored in this paper.

2 Materials and Experimental Methods

2.1 Materials and Mixture Design

ASTM Type I/II Portland cement, tap-water, river sand, and crushed limestone with a nominal maximum aggregate size of 0.019 m were used in this study. The goal of the study was to create a conventional concrete mixture that can be 3D printed without additives.

The mixtures used in this study had a water to cement ratio (W/C) of 0.4 by mass. The concrete rheometer used in the study required a slump of at least 0.075 m and hence a relatively high W/C was chosen to get a slump of about 0.18 m for the concrete mixtures. The mixture proportions are shown in Table 1.

Table 1. Volume proportions of the concrete mixtures

Mix ID	Volume (% of total concrete vol.)						% Sand (of total agg., by vol.)
	Paste	Air	Agg.	Mortar	Sand	Coarse agg.	
A	35	3	62	55	20	42	32
B	35	3	62	60	25	37	40
C	35	3	62	65	30	32	48
D	35	3	62	70	35	27	56
E	35	3	62	75	40	22	65
F	97	3	0	0	0	0	0
G	67	3	30	100	30	0	100

2.2 Method

The static yield stress was measured with an International Center for Aggregate Research (ICAR) concrete rheometer [15]. Figure 1 shows the modified rheometer used to measure the yield stress of concrete during vibration. The modification included placing the concrete container on a vibration Table (60 Hz frequency, 0.001 m maximum amplitude) and securing it with ratchet clamps and separating the torque meter by suspending it over the bucket instead of placing it on it [13].

The static yield stress of the concrete was measured at pre-determined time intervals. The static yield stress before, during, and after vibration was measured. The time interval between vibration was selected to mimic the 3D printing process such that a new layer is deposited every 7 min. The first vibration period was between 20.5 min and 22 min. Three static yield stress measurements were carried out during each of these vibration periods.



Fig. 1. Modified concrete rheometer.

3 Results and Discussion

3.1 Effect of Aggregate on Yield Stress

To test the role aggregates have on the yield stress of cementitious mixtures, three mixes were tested. Mixes C, F, and G represented concrete, paste and mortar respectively. The yield stress of each and the effect of vibration has on it is shown in Fig. 2.

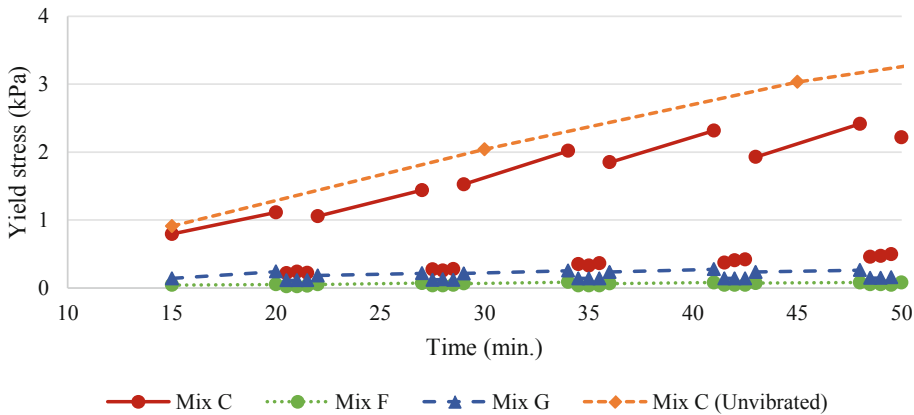


Fig. 2. Yield stress of cementitious mixtures with varying aggregate content.

The yield stress of concrete increases with an increase in the volume fraction of aggregates [11]. The concrete mix (Mix C) was found to have significantly higher yield stress than the mortar mix (Mix G) which had the same volume of sand. Both of these in turn had yield stress greater than the cement paste mix (Mix F). The yield stress of the mixes reduced during vibration. This is particularly pronounced in the case of mix C. The drop in yield stress was observed to be instantaneous and reversible. At the end of the vibration, the yield stress is almost completely recovered. When Mix C was tested at regular intervals without disturbance, it continued to gain yield stress with time at a slightly higher pace as compared to the concrete which was periodically vibrated.

These results indicate that incorporating coarse aggregate in 3D printable concrete could be beneficial by providing a significantly higher green strength. The higher yield stress while beneficial for post-printing properties like greater layer heights, shape stability and shape retention, is detrimental during the extrusion process. But the results here show that vibration can help overcome the increased yield stress caused by the incorporation of coarse aggregates. The yield stress of concrete can be reduced to the order of mortar yield stress with vibration.

3.2 Effect of Aggregate Packing on Yield Stress

In concrete 3D printing, it is beneficial to have low yield stress during the extrusion process and high yield stress after. With a vibration-based concrete 3D printer, the goal would be to increase the yield stress when concrete is not being vibrated and to reduce it during vibration. Five mixes with the same total aggregate content but varying sand to coarse aggregate ratios were tested to see the effect vibration has on concrete with varying aggregate packing fraction. The results are shown in Fig. 3.

For a given aggregate content as seen in Fig. 3, the yield stress is higher at lower sand content (Mix A) due to greater coarse aggregate physical interlock and at higher sand content (Mix E) due to increased paste demand because of the increased surface area of sand. The packing fraction of the mixes is also influenced by the sand content, void ratio is lower at intermediate sand content and higher in other cases. Increased void ratio leads to cement paste filling the voids and reducing the paste available for coating aggregates, thus increasing frictional interlock. From Fig. 3, we see that at intermediate sand content (Mix C), the yield stress is lower. During vibration, the yield stress reduction is slightly lower for Mix E and this could potentially be due to the reduced coarse aggregate content. Since vibration reduces yield stress by disrupting the physical contact network, reduction in coarse aggregate causes reduction in the contact network and hence yield stress is not lowered by vibration to the same extent as the other mixes shown here [11, 14].

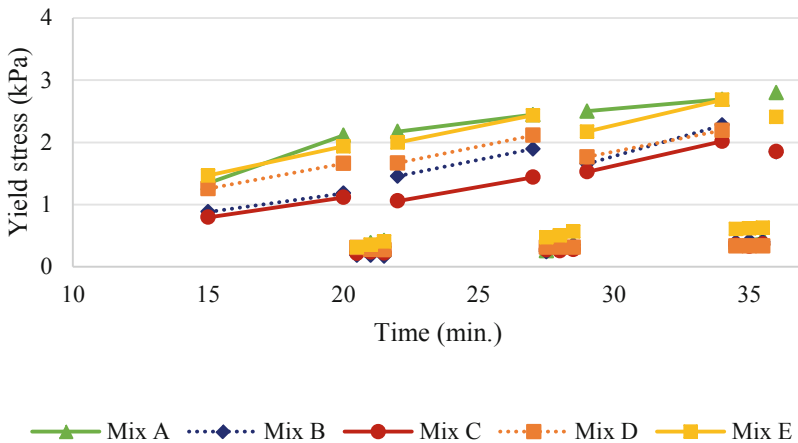


Fig. 3. Yield stress of concrete with varying coarse aggregate volume fractions.

The mixes tested in this study were limited because the rheometer required the slump to be greater than 0.075 m. Ideally, for concrete 3D printing using vibration-based extrusion, a no-slump concrete with higher yield stress should be considered. By using a vibrating nozzle, this no-slump concrete can be extruded and the lack of vibration once the concrete leaves the nozzle will cause it to regain its high yield stress, allowing it to hold its shape and the weight of subsequent layers. Delivery of the

no-slump concrete to the nozzle is one of the potential issues with this proposed concrete 3D printing method. The impact of vibration will be more complex to implement if the concrete is pumped before it reaches the nozzle and is an area that will need to be addressed moving forward.

4 Conclusion

In this study, a new approach to concrete 3D printing is proposed. The benefits of incorporating coarse aggregates in 3D printable mixtures and material delivery by vibration is explored. By using coarse aggregate in 3D printable mixtures, the yield stress increases considerably due to packing and interlock of aggregates. The higher yield stress will improve printing parameters such as shape stability and retention. It will also allow for faster printing. By using vibration, the yield stress of concrete can be overcome. This drop in yield stress during vibration is immediate and completely recoverable. By using vibration in the extrusion process, the high yield stress of concrete can be manipulated for material delivery.

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Prediction of the Yield Stress of Printing Mortar Ink

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Abstract. The development of printable cement-based materials is a high priority in the field of 3D printing for construction. There are many admixtures available for the design of the printing mortar ink which can influence the wet and final properties of the mortar. In this work, artificial intelligence has been utilized to predict those properties and guide the dosage of each admixture. The algorithms were developed from a factorial experimental plan. The mortar investigated consists of cement blended with silica fume to reduce the embodied carbon of the mixture. The selected admixtures were a superplasticizer, a viscosity modifying agent, nano-clay, C-S-H seeds and an accelerator with a water-reducing effect. A rotary rheometer was used to measure the viscosity and the dynamic yield stress of both mortar and cement-paste mixtures. Additional tests were conducted such as the small Abrams cone and the ASTM C1437 flow test. Several predictive algorithms were developed and compared, in which artificial neural networks were used. Furthermore, to enhance the performance of the neural network, a genetic algorithm was used to optimize the network parameters. To evaluate the performance of the models, the normalized root mean square error (NRMSE), and coefficient of determination (R^2) were calculated. This approach is a single-objective prediction which yields promising capability to predict the wet properties of both mortar and cement pastes, which can be later expanded into a multi-objective approach.

Keywords: Artificial neural networks · Genetic algorithms · Wet properties · Mix design · 3D printing

1 Introduction

In recent years, artificial intelligence (AI) has been increasingly utilized to solve complex problems across many engineering sectors. Civil engineering is among them, where AI has been applied for the prediction of concrete properties, such as compression strength, drying shrinkage, filling capacity, concrete durability, segregation and slump [1–6]. The majority of the studies in this field use artificial neural network algorithms (ANN), tree-based models, and fuzzy logic. The combination of AI methods with optimization techniques is also promising. ANN has been implemented along with the whale algorithm or the multi-objective grey wolves technique, whereas the adaptive network based fuzzy inference system has been used with genetic algorithms [2–4].

These studies confirm that AI techniques are a promising avenue to predict the properties of concrete materials.

In this study, the main objective is to develop ANN models that can predict the wet properties of mortar and cement-paste mixes. Two different methods were compared: the leave-one-out cross validation method and the genetic algorithm (GA) optimization technique which divides the available dataset into training and testing data with proportions of 70% and 30%, respectively. The GA technique was applied to investigate an increase in the prediction performance of the ANN model in searching the optimal parameters. Sixteen formulations were available from a previous study of Charrier and Ouellet-Plamondon [7] where six early age property measurements were conducted, such as rheological and slump tests. The objective of the present study is the prediction of those six properties, namely the yield stress, viscosity, and mini-slump test for cement-paste mixes and slump, flow and deformation tests for mortar mixes for 3D printing applications. The coefficient of determination (R^2) and the normalized root mean squared error (NRMSE) were employed to evaluate the effectiveness of the proposed models and to compare the two different methods.

2 Materials and Testing Methods

2.1 Materials and Mix Design

Binder and Admixtures. The cement that was used in this study is the GUb-8SF which is a binary cement with silica fume and a specific gravity of 2.8. A local sand was selected with specific gravity of 1.65 and the water used was tap water. The selected admixtures were five in total; a superplasticizer (SP), an accelerator (A), the C-S-H seeds (X), nanoclay (C), and a viscosity modifying agent (VMA). The SP, A, X were added to control the workability of each mixture. The A and X are strength-enhancing admixtures which are also known to improve cement hydration. Finally, the VMA and C were used to increase the stability of the mix. The solid content of the admixtures was determined according to ASTM C494 [8]. Further details can be found in the published study.

Mix Design. For the mortar mixes, the sand/cement ratio was selected to be 1.8. Based on literature this ratio results in a mortar mixture with acceptable pumpability-extrudability. The water/cement ratio was a fixed proportion of 0.345 for all of the mixes, both for cement-paste and mortar mixes. In this ratio, the water content of each admixture was included. The water content of each admixture was determined by measuring the residue of each admixture with oven drying, according to ASTM C494 [8]. Furthermore, the dosage for each admixture was determined based on the literature review [7] and experimental tests with different dosages that were conducted in a preliminary study. The quantities of SP, C, A, X and VMA used were 0.26%, 0.50%, 0.70%, 0.30% and 0.004% of the cement weight, respectively. A two-level full-factorial design was implemented for the experimental design, where the admixtures except for SP were either present in the aforementioned amounts or absent. It is always preferable to do a factorial design. The only exception is if the admixtures do not

interact with each other with absolute certainty. Factorial design can also reduce the number of runs necessary, resulting in prompt convergence. The SP was included in all mixes to reduce the water content. Hence, the total amount of the mixes was $2^4 = 16$. Finally, all the admixtures were added to the water just before the addition of the binder, apart from the C admixture which was dry mixed with the binder. The mixing procedures for the cement paste were made according to ASTM C1738 [9]. The 16 mixes and the six testing methods are explained in [7, 10].

3 Artificial Intelligence

In 3D concrete printing a common challenge is the development of a suitable mixture. Some of the most important properties of the mixture are the flowability, extrudability, and buildability [11–13]. However, in general those properties tend to be contradictory to each other. In order to address this problem, artificial intelligence can be utilized to develop the best possible mixture. Compared to linear and quadratic models, machine learning provides better predictive performance of the concrete mixture properties, such as compressive strength and slump [3]. At an early stage of the study, the two most prevalent algorithms were compared, the random forest (RF) and the artificial neural network algorithms (ANN). The preliminary results showed better accuracy of the ANN. Thus, only the results of the latter are discussed herein in detail.

3.1 Algorithms

Neural Network. The ANN can be described as an interconnected system of nodes inspired by the biological neural networks of the human brain. The ANN consists of three basic components, namely the input, hidden, and output layers. This model is trained in order to predict the output from a provided input. Compared with traditional computational models, the advantages of ANN are that it does not require predefined constraints and it is powerful in large data problems. Furthermore, ANNs can observe a pattern during training or identify complex nonlinear relationships in the data itself. ANNs have been used in concrete mixture design where the input and output layer nodes are decision variables and objectives, respectively. Training the network with a dataset changes the weights between the nodes and increases the predictive performance [3].

Evaluation. In order to evaluate the performance of the models, the normalized root mean square error (NRMSE), and coefficient of determination (R^2) are calculated. The NRMSE is the normalized mean squared difference between targets and outputs, and R^2 describes the correlation between outputs and targets. In brief, lower NRMSE and higher R^2 (with a range between 0 and 1) show better accuracy of the model.

3.2 Methodology

Cross-validation: Leave-one-out. Following the approach of [10], the first algorithm that was developed in MATLAB was a neural network with the leave-one-out cross-validation method. As the author mentions, this method was chosen in order to avoid overfitting of the model. The available dataset was 16 different mixes; therefore, the training of each network was made from the 15 out of the 16 samples in total and the remained sample was used for testing. As a result, the developed algorithm produced 16 different networks which were compared by calculating the NRMSE and R^2 . Linear, quadratic and cubic regressions were performed to achieve better results. Furthermore, each network is consisted of three layers, namely the input, output and one hidden layer with ten neurons. The input neurons were the types of admixtures that were used, whereas the output is one property of the material, such as the yield stress, viscosity or mini-slump. The selected training function of the network updates the bias and weight values according to Levenberg-Marquardt optimization. This minimizes a combination of squared errors and weights and then determines the correct combination to produce a network that generalizes well. The process is called Bayesian regularization back-propagation [14].

Optimization Algorithm and 70/30 Rule. A testing plan is used to ensure that the evaluation provides realistic estimates of model performance on unseen data. Generally, one of the main steps is to split the data into training and testing sets. The proportions of split may vary depending on the project, although 70/30 is the most common, where 70% is for training and 30% for testing. In the first few attempts to apply this methodology to this network, the number of the hidden layers and neurons along with the training method, remained the same as the ones of the leave-one-out-cross validation method. The genetic algorithm was later selected in order to optimize the parameters of the network depending on the property to be predicted. The genetic algorithm (GA) is one of the oldest and most widely used evolution algorithms (EA). GA is inspired by the natural evolution of species, where the population adapts and evolves based on the environmental conditions. It consists of a population of individuals in which each one represents a potential solution to the problem. Similarly, to other EAs, a GA develops a random population of candidate solutions and iteratively forms subsequent populations of solutions by the selection, crossover, and mutation of a portion of the best solutions. The number of the total population can be gradually increased in each iteration [3]. The parameters that were tested to improve the predictive performance of the neural networks were the number of hidden layers, the number of neurons of each hidden layer, the number of neurons of the output layer and the training method. Since the number of the neurons in the output layer was a parameter, single and multi-objective predictions were performed. The goal of the genetic algorithm was to simultaneously maximize the R^2 and minimize the NRMSE. The second selected training function is a network training function that updates bias and weight values according to Levenberg-Marquardt optimization. Typically, it is the fastest backpropagation algorithm, despite requiring more virtual memory than other algorithms [14].

4 Results and Discussion

The first approach was to use linear regression and to compare the 16 different combinations of the training and testing sets. The linear regressions of the networks for predicting the properties of the cement paste are shown in Fig. 1. The black dots represent the training data, whereas the red dot is the testing sample. The best performance for the yield stress was achieved in the 14th network, with $R^2 = 0.999$ and NRMSE = 0.013. The testing sample was the 3rd mix and the rest were used for training the network.

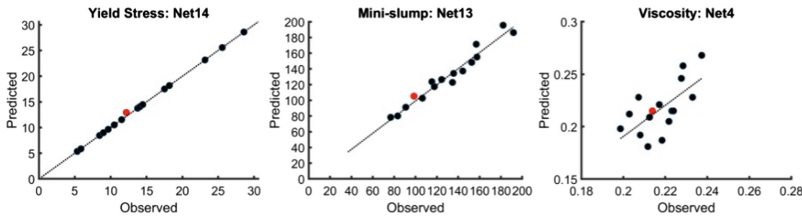


Fig. 1. The linear regression that was performed for the 14th network of yield stress (a), 13th network of mini-slump (b) and 4th network of viscosity (c) of the cement paste.

Moreover, the best network for predicting the mini-slump was the 13th network, with $R^2 = 0.958$ and NRMSE = 0.054. The testing sample was the 4th mix and the rest were used for training the network. However, concerning the network for the viscosity, the predictive performance was below an accepted value, as the R^2 and NRMSE were 0.44 and 0.084 respectively (Fig. 1).

Predicting the properties of the mortar mixes was also feasible. The predictive performance of the networks was even better than those of the cement paste. Particularly, in the 16th network with the deformation as the only objective, the R^2 was greater than 0.999 and the NRMSE was 0.002. Concerning the flow, the best network was the 3rd with R^2 and NRMSE being 0.97 and 0.0018 respectively. As for the slump, which is the third and final property measured for the mortar mixes, the 15th was the best network in which the R^2 was 0.994 and the NRMSE was 0.033 (Fig. 2).

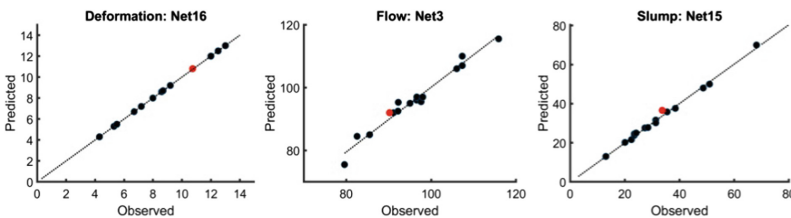


Fig. 2. The linear regression that was performed for the 16th network of deformation (a), the 3rd network of flow (b) and 15th network of slump (c) of the mortar.

The linear regressions of all the properties had strong correlation except for the viscosity of the cement paste. With the aim to develop a better network for the viscosity, a second approach was attempted by comparing linear, quadratic and cubic regressions. This approach was not only used for the viscosity, but also for all of the six properties to observe if there will be any further improvement in performance. The best performance among the cement paste properties was achieved by the 14th network for predicting the yield stress, with $R^2 = 0.999$ and NRMSE = 0.013 with quadratic regression (Fig. 3a). However, the performance was the same as the linear regression. The testing sample was the 3rd and the rest was used for training the network.

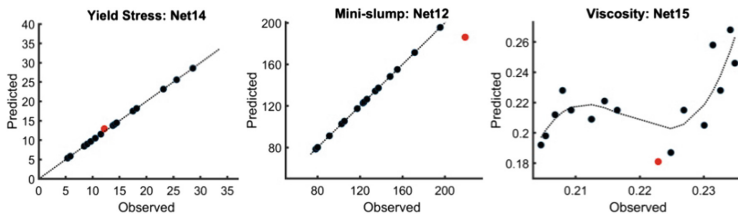


Fig. 3. The quadratic regression that was performed for the 14th network of yield stress (a) and the cubic regression for the 12th network of mini-slump (b) and the 15th network of viscosity (c).

Moreover, the best network for predicting the mini-slump was the 12th network, with $R^2 = 0.994$ and NRMSE = 0.063 with cubic regression. The testing sample was the 5th and the rest was used for training the network. In this non-linear network, there was a minor improvement in the performance compared with the linear regression. Furthermore, the best network for predicting the viscosity of the cement paste was the 15th network, with $R^2 = 0.687$ and NRMSE = 0.094 with cubic regression (Fig. 3). The regression showed almost a strong correlation, $R^2 \sim 0.7$. Thus, it was considered acceptable. The testing sample was the 2nd and the rest was used for training the network.

The best performance among the mortar properties was achieved by the 16th network for predicting the deformation, where the R^2 was greater than 0.999 and the NRMSE was 0.002 with quadratic regression (Fig. 4a). However, the performance was also the same as the linear regression. The testing sample was the 1st and the rest was

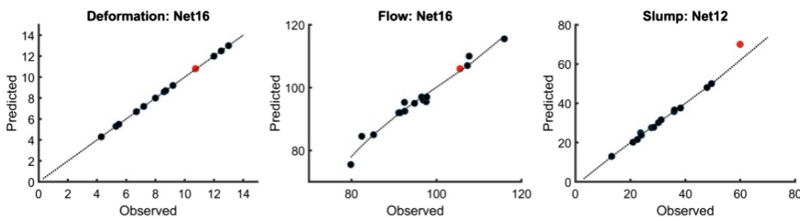


Fig. 4. The quadratic regression that was performed for the 16th network of deformation (a) and the cubic regression for the 16th network of flow (b) and 12th network of slump (c).

used for training the network. Concerning the network for the flow, the 16th was the best network where the R^2 and NRMSE were 0.976 and 0.0017 respectively with cubic regression. The performance was slightly improved, and the testing sample was the 1st. As for the slump, the best network was the 12th with R^2 equal to 0.997 and NRMSE 0.079 with cubic regression (Fig. 4). The testing sample was the 5th, with a modest improvement over the linear regression. In brief, the leave-one-out cross-validation method was applied successfully for both the mortar and cement paste properties, and the results of the evaluation methods were acceptable. However, despite the good results for the R^2 and the NRMSE, the figures above, such as Fig. 3b of the mini-slump or Fig. 3c of the viscosity, also reveal a noticeable error between the prediction and observed values of the testing sample. This implies that the predictive performance is not realistic and that most of the networks are overfitted. This fact can be explained by the big imbalance between the training (94%) and testing (6%) data.

In order to face the above-mentioned problem, new networks were created with a better split of the available dataset. Based on the literature, the most common proportions of the two sets, training and testing, is 70 and 30% respectively. However, a better balance of training and testing data alone does not guarantee an improvement in the model. For this, it is essential to use a suitable algorithm to discover the optimal parameters of the network. To overcome this problem, the genetic algorithm was used (Fig. 5a). The maximum generations of the algorithm were selected to be 50, the number of candidate solutions of the first generation was 80 and at every new generation the number was increased by 40. Depending on the cement parameter being modeled, different parameters were considered to be the best for each individual network. However, there were a few common parameters that were used in all networks. Specifically, the best training method was the Levenberg-Marquardt, the performance method was the mean squared error, and the networks with only one hidden layer performed better (Fig. 5b). The data was divided into two parts, the training and testing. However, the division was conducted prior to entering the data to MATLAB network function. Hence, only the training data was input to the network and the 'dividetrain' function was selected to assign all data of the training set only. Testing of the network was performed with linear regression, and the results were used as input for the genetic algorithm. Finally, in order to reduce the amount of time required for the overall algorithm, the number of the maximum epochs of each network was selected to be 400.

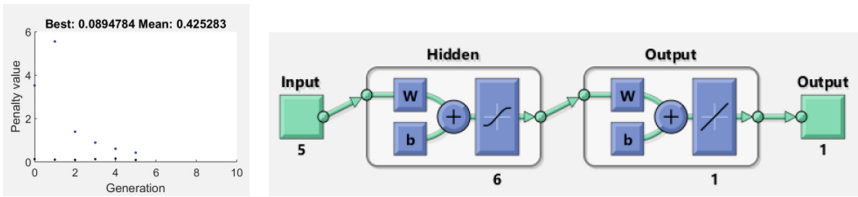


Fig. 5. Examples of the genetic algorithm and of a network in (a) and (b) respectively. In (a), the results of the initial and first four generations are depicted. In (b), the general form of a network with three layers is shown; the input, output and one hidden layer with 6 neurons.

The number of output neurons, or objectives, was also a parameter. Several attempts were made to create multiple output networks; for instance, training two networks in total, one for the cement paste's properties and another one for the mortars where each one had three objectives, or only one network with six objectives. However, the best predictive performance was achieved when each network had only one objective, hence the final number of the networks that were developed were six in total. As a result, each property of the mortar and cement-paste mixes has a separate optimized network. In the following discussion, each network is explained separately along with figures of the linear regression. In each figure, the black dots depict the training data set, 11 mixes, whereas the red dots, remaining 5 mixes, are the testing dataset. Finally, the training and testing data were randomly selected every time at each iteration of the genetic algorithm. However, based on the final results, the best mixes for training all networks were the 2nd, 3rd, 5th, 7-11th, 13-15th mixes and the rest were used for testing the network.

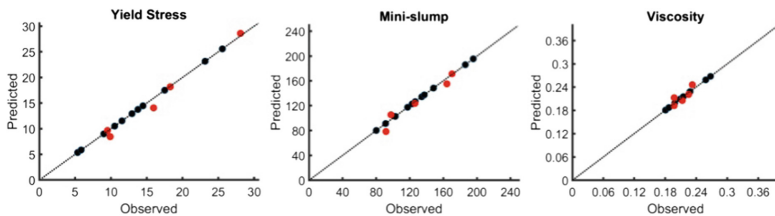


Fig. 6. The linear regression that was performed for the network with the yield stress (a), the mini-slump (b), and viscosity (c) of the cement paste as the only objective.

For the best network with the yield stress as the only objective, the R^2 was 0.9924 and the NRMSE was 0.0629. In order to achieve those results, the number of the neurons on the hidden layer was six in total. Concerning the network for the mini-slump, the R^2 and NRMSE was 0.9833 and 0.00263, respectively. In this network, the best performance was achieved with the number of the neurons on the hidden layer to be ten in total. As for the viscosity, the improvement was evident as the R^2 was 0.9426 and the NRMSE was 0.023. The network performed better with eleven neurons in total on the hidden layer (Fig. 6).

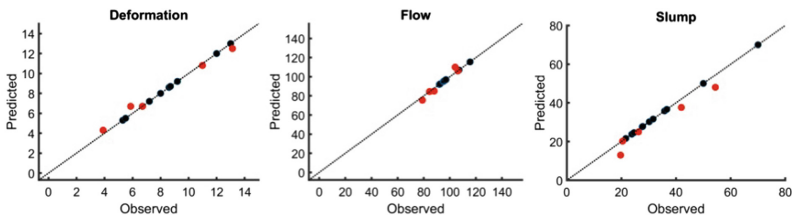


Fig. 7. The linear regression that was performed for the network with the deformation (a), flow (b) and the slump (c) of the mortar.

Furthermore, for the best network with the deformation as the only objective, the R^2 was 0.9921 and the NRMSE was 0.0263. In order to achieve those results, the number of the neurons on the hidden layer was seven in total. For the network for the flow, the R^2 and NRMSE were 0.9722 and 0.00176, respectively. In this network, the best performance was achieved with the number of the neurons on the hidden layer to be seven in total. As for the slump, which is the third and final property measured for the mortar mixes, the R^2 was 0.9715 and the NRMSE was 0.0685 (Fig. 7). The network performed better with four neurons in total on the hidden layer. The summary of the results is presented in Table 1.

Table 1. Summarizing all the results of leave one out cross validation method (1st) and 70/30 method with genetic algorithm (2nd)

Mixture	Test/Property	R^2			NRMSE		
		1 st Method		2 nd Method	1 st Method		2 nd Method
		Linear	Quadratic, cubic	Linear	Linear	Quadratic, cubic	Linear
Cement paste	Yield stress	0.999	0.999	0.9924	0.013	0.013	0.0629
	Mini slump	0.958	0.994	0.9833	0.054	0.063	0.0263
	Viscosity	0.44	0.687	0.9426	0.084	0.094	0.023
Mortar	Deformation	>0.999	>0.999	0.9921	0.002	0.002	0.0263
	slump	0.994	0.997	0.9715	0.033	0.079	0.0685
	Flow	0.97	0.976	0.9722	0.018	0.017	0.0176

5 Conclusion and Future Work

Based on the evaluation methods that were applied, the leave-one-out cross validation method with quadratic and cubic regression perform slightly better for most properties. On the other hand, the 70/30 method with GA can predict the viscosity of the cement paste better than the cross-validation method. The viscosity was the most difficult property to be predicted without changing the controllable factors of the network, such as the number of the neurons in the hidden layer. Finding the right values of those factors would be hard to be achieved without the GA method. However, the proportion of the training data of the dataset was different, specifically 96% and 70% respectively on the two methods. As a general conclusion, predicting properties for new mixes is possible by employing these two methods, although, the second method is the suggested one. Despite the fact that the available dataset was small, it was adequate for training and validating the developed networks. However, the testing of those networks will be made with new unseen data. Hence, as a next step, the prediction accuracy of the developed networks will be validated by forming new mixtures and testing them in the lab. More data will be added with the aim to have a large and diverse data set. Additionally, new attributes and objectives will be added by employing new tests on

cement pastes and mortars, such as calorimetry and compression tests. Finally, multi-objective optimization algorithms will be developed with the aim to design optimum mortar mixes suitable for 3D printing applications, by achieving the desired properties, reducing the overall cost and forming more eco-friendly mixes.

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Dynamic and Static Yield Stress Determination of Cementitious Paste with Admixtures

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Abstract. The 3D printing of cementitious material requires an understanding of the printing material's rheological properties, especially yield stress and viscosity. The ability to adjust and control these properties in the 3-D printing process represents a breakthrough for the construction sector. The aim of this paper is to experimentally determine the dynamic yield stress and static yield stress of cementitious materials with admixtures. Unlike conventional rheometer geometries, the National Institute of Standard and Technology (NIST) spindle geometry is used in this work for the measurement of both yield stresses. While dynamic yield stress was measured by increasing and decreasing the rotational velocity, the static yield stress was characterized by two methods: the torque increase method and the constant rotational speed method. For both yield stresses, a total of 16 mixtures were studied in a factorial experimental design of the chemical admixtures. The impact of each admixture has been highlighted. The structural build up was assessed through the structuration rates. The temperature effect on the early age properties was studied for the most promising formulations.

Keywords: Cement paste · Admixtures · Dynamic yield stress · Static yield stress · Structural build up · Temperature

1 Introduction

In recent years, many industrial sectors have innovated in manufacturing methodology to take advantage of new technology. However, the construction field continues to be limited to conventional formwork methods for precast concrete and cement-based products. Developed in the 2000s, 3-D printing and additive manufacturing present a paradigm shift in production methodology. With computer assistance, 3-D printing can overcome difficulties of conventional formwork-based techniques, such as precise deposition, material solidification process and material volume quantification [1]. Furthermore, 3D-printing has the potential to reduce the manufacturing time by replacing both the casting and molding production steps [2]. The printing process consists of material extrusion and layer by layer deposition. Utilization of this technique necessitates a deeper understand of how to control the material flow. Determining the mechanical conditions for flow in cementitious materials is complicated by

the use of admixtures which modify the rheological and mechanical properties [2]. The flow conditions vary with formulation parameters such as the type of admixtures, the time of addition [3], and the physical form of the mixture [4]. For consistent extrusion rates at reasonable pressures, the mixture must exhibit a certain degree of fluidity. In addition, the static integrity of a material layer must exceed a certain level to enable the deposited layer support the subsequent layers [2]. While the fluidity of the material may depend much on its viscosity, the stability of the printed layer is a product of the yield stress. At the microscopic scale, the yield stress is a measurement of the force required to overcome the interparticle attractions within the suspensions of the cementitious material [5]. Due to thixotropic nature of cementitious pastes, two different yield stresses are considered when describing the material's rheological properties: the dynamic yield stress and the static yield stress. In this work, the yield stress measurements were carried out using a rotational rheometer equipped with a spindle geometry [6]. Calibration methods [6] were followed to determine both dynamic and static yield stress of the mixtures obtained from combinations of different admixtures. The structural build up was assessed using linear equations developed in others works [6, 7]. Finally, the effect of temperature on the dynamic yield stress was explored.

2 Materials and Methods

The experiments in this work were conducted with 8% by weight silica fume added to Portland cement in a mixture known as GUb-SF with a specific gravity of 2.8. Sixteen different formulations were designed from a combination of admixtures: superplasticizer (SP), accelerator (A), C-S-H seeds (X), nano-clay (C) and viscosity modifying agent (VMA). Design details of the formulations are given in Table 3 of [2]. Based on the preliminary studies conducted with the paste and per the recommendation of the concrete producers, a water-cement ratio of 0.345 was chosen with tap water. As most of the admixtures take the form of aqueous solutions or suspensions, the addition of water (effective water quantity) was adjusted to account for this and maintain this constant ratio. The admixtures modify the rheological properties of the fresh cementitious paste to the requirements of the 3-D printing process as studied by several researchers in the past [3, 4]. Microstructural inhomogeneities are known to cause variations in rheological properties [8]. For this reason, it is important to select a suitable mixing procedure to maximize homogeneity. The mixing procedure certified by NIST was followed in this study [6]. First, the appropriate amount of water and admixtures was poured into the mixer at room temperature of 23°C. The cement was added within 60 s. The mixture is blended with a high-speed mixer at 10 000 rpm for 30 s. Following this, a rest time of 150 s is given to the paste before a final mixing step for 30 s at the same speed. The measurement of the dynamic yield stress was initiated 5 min after the mixing procedure. A total of 35 measurements were recorded by increasing and decreasing the angular velocity in the range of 0.1 rpm to 100 rpm in a hysteresis loop. The full test was conducted in 17 min with a measurement every 30 s or until the torque stabilized. From the collected data of the 16 mixtures, the shear stresses were computed as functions of the shear strain for each increasing and decreasing angular velocity. The conversion of angular velocity and torque to shear

stress and shear strain, respectively, was possible from NIST calibrated models with the calibration factors K_τ and K_μ , 11939 Pa/Nm and 2.190, respectively.

3 Results

3.1 Dynamic Yield Stress

The dynamic yield stress was calculated as the intercept of the linear regression of the stress-strain curve of decreasing angular velocity for each of the 16 formulations. The design and composition of the 16 mixtures is described in Table 3 of [2]. The results of these calculations are shown in Fig. 1, labeled by the acronyms of the admixtures present in the formulation. The lowest dynamic yield stress was observed to be 5.35 Pa in mix 5, which incorporated the ready-mix accelerator. The highest value was in mix 12 at 28.60 Pa.

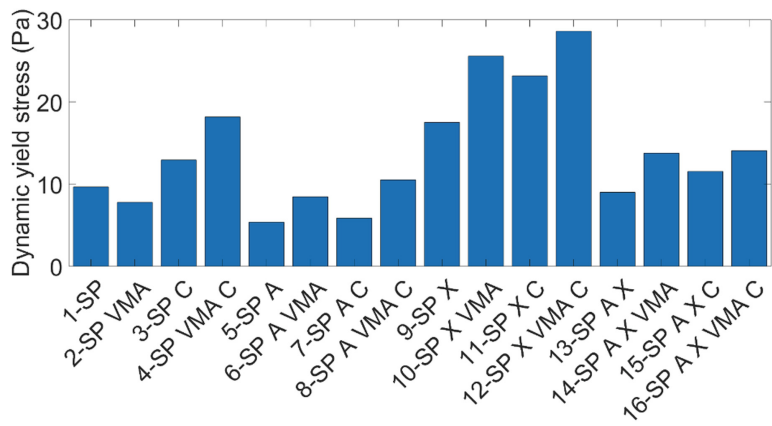


Fig. 1. The dynamic yield stress of each of the formulations compared in this study

3.1.1 Effect of Temperature

The effect of the temperature on the dynamic yield stress was studied on a few arbitrarily selected mixtures as detailed in Fig. 2. The measurements were carried out at the temperatures of 5 °C, 15 °C, 23 °C, 30 °C and 40 °C. Below the temperature of 30 °C, a fluctuation of the dynamic yield stress was observed for mix 7 (SP A C) and mix 16 (SP A X VMA C). For mix 13 (SP A X) and mix 14 (SP A X VMA), the yield stress increased monotonically in the temperature range. The highest value, approximately 30 Pa, was recorded at 40 °C for mix 16 (Fig. 2). In contrast, the plastic viscosity of the pastes decreased in the range of 5 °C to 40 °C.

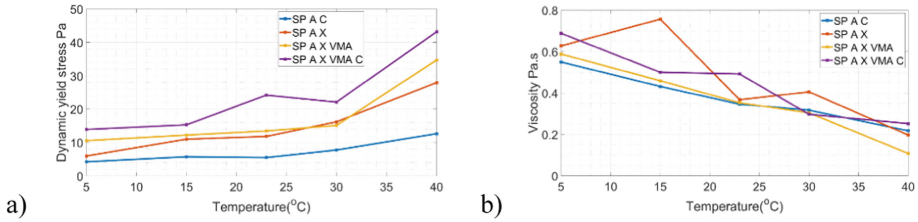


Fig. 2. The effect of temperature on the a) dynamic yield stress and b) viscosity on selected mixtures

3.2 Static Yield Stress

The results of the static yield stress tests of the mixtures are presented below. Measurements were completed at 13, 31, 51 and 71 min. After each test, a rest time was allowed for the mixture to undergo structural build up for the subsequent measurement. The calibration factors used in the calculation are 11916.213 Pa/Nm and 2.711 for K_τ and K_μ , respectively.

3.2.1 Torque Increase Method

Data was collected every 30 s by increasing the torque from 0 to 8 Nm, or until the angular velocity reach 150 rpm, for a total of 60 measurements recorded over the range of the torque. Figure 3 shows the evolution of static yield stress over time for the different mixtures. As expected, most mixtures exhibit a static yield stress increase with time. For example, the static yield stress of mix 1 (SP) at the time of 53 min experienced an average increase of about 27 Pa. However, a reduction of approximately 30 Pa was observed for some mixtures, such as mix 5 (SP A) and mix 7 (SP A C).

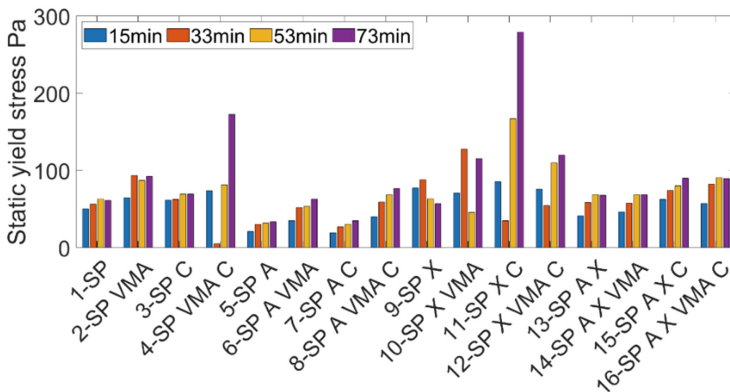


Fig. 3. The static yield stress of mixtures at different times by the torque increase method

3.2.2 Constant Speed Method

Figure 4 shows the time dependence of the static yield stress of 16 different mixtures by the constant speed measurement method. The static yield stress of most of the mixtures did not increase with time, except mix 4 (SP VMA C) and mix 9 (SP X) to mix 12 (SP X VMA C) where a significant increase was observed. For these five mixtures, there is an average increase of approximately 160 Pa between the 33rd and 53rd min and more than 300 Pa between the 33rd and 73rd min. The structuration rates for these five mixtures are given in Table 1.

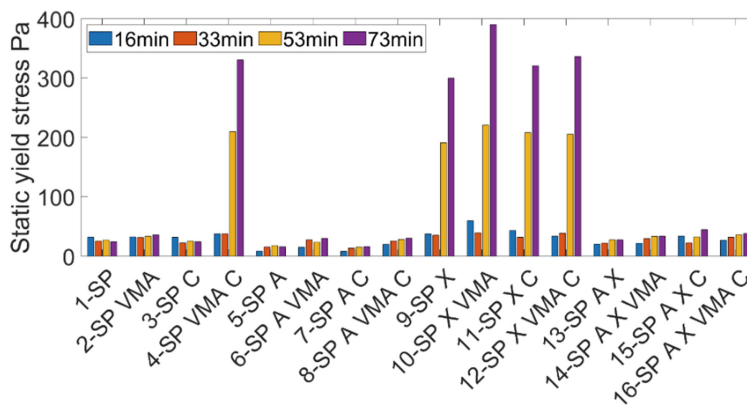


Fig. 4. The static yield stress of 16 mixtures at different times by the constant speed method

Table 1. Structuration rate for select mixes as measured by the constant speed method (Pa/min)

	Mix 4	Mix 9	Mix 10	Mix 11	Mix 12
16 min–33 min	0.0057	–0.1257	–1.2051	–0.6752	0.2980
33 min–53 min	8.6069	7.7885	8.9300	8.7885	8.3365
53 min–73 min	6.0302	5.4020	8.5845	5.6645	6.5110

4 Discussion

The ability to modify and fine-tune the rheological properties of a material is essential for 3D printing. The 16 formulations studied in this work lay the groundwork for the experimentation required to create a full rheological adjustment function for use in 3D printing applications. As was studied here, this function must consider the admixture proportions, temperature effects, and time dependence.

Figure 1 shows the dynamic yield stress variation with the chemical admixtures. Mix 1 (SP) is taken as reference since it contains only the superplasticizer (SP). C-S-H seeds (X) and nano-clay (C) are responsible for formulations with the highest values of dynamic yield stress such as mix 12 (SP X VMA C). The C-S-H seeds alone contribute

to the strengthening of the cement paste which can be seen in mix 9 (SP X) of Fig. 4. A decrease in the dynamic yield stress was observed in some mixtures due to the accelerator (A) and the viscosity modifying agent (VMA). The accelerator used in this study was designed for ready-mix concrete which combines an accelerating effect with a lengthened induction period to allow for transport. For this reason, the accelerator has the expected effect of prolonging the fluidity of the paste. It can still be useful for 3D printing, to prepare batches in advance. From this it is interpreted that the measurements were conducted before the hydration peak was reached for the formulations with the accelerator.

Temperature was observed to have a significant impact on the dynamic yield stress. For the arbitrarily selected mixtures, the temperature was shown to positively increase the dynamic yield stress in the range of 5 to 40 °C (Fig. 2). While the dynamic yield stress increases up to 40 °C, the viscosity was observed to reduce significantly for all the selected mixtures. The fact that both dynamic yield stress and viscosity increase and decrease, respectively, with temperature is surprising. However, it has been reported in literature that the temperature is responsible for two opposing effects in the yield stress of cementitious material [9, 10]. First, the yield stress decreases with temperature due to accelerated particles mobility and aggregation breakdown [9]. Second, elevated temperature accelerates binder hydration which increases the yield stress [9, 10]. Temperature acceleration of hydration reactions is well known in the literature for cement and other binders [10–12]. This duality explains the seemingly contradicting expectations of the impact of temperature. The viscosity decreases due to deagglomeration, while the yield stress increases due to accelerated hydration. This suggests temperature variation could be incorporated in 3D printing process design for reducing slump during deposition and rheological properties adjustment. However, further study is needed to more thoroughly understand the mechanisms behind the dynamic yield stress and viscosity trends with temperature. In addition, it will be important to document the influence of temperature on the structuration rate as the structure of printed layers is known to be affected by hydrostatic pressure over time [4, 13, 14]. The time between two consecutive printed layers is variable with the 3D printing technique and, as identified in this example, is significant to the material stability. Future work must elucidate the temperature conditions to optimize the material properties for suitable print stability.

With regards to the static yield stress, a large gap was observed between the two methods of measurement as detailed in Fig. 3 and Fig. 4. In general, the torque increase method, Fig. 3, measured only a modest impact of the admixtures on the static yield stress. The small increase with time can be attributed to yield stress development during the rest time rather than the chemical effect of the admixtures. The exceptions to this trend in time are the mix 5 and mix 7 which are a consequence of the accelerator in those formulations by the phenomenon described earlier. However, when the accelerator is used in combination with the other admixtures, the same general trend is followed, as in mix 8 (SP A VMA C) and mixes 13 to 16. In contrast to most of the measurements, a considerable increase of static yield stress was recorded for mix 4 (SP VMA C) and mix 11 (SP X C) between the 53rd and 73rd min of rest time. Notably, for the same mixtures there is a reduction in yield stress between the 33 and 16 min measurements. This is most likely due to a history effect from the previous

measurement. For most of the mixtures, the viscosity was low enough for the applied torque to cause no observable shift in angular velocity. However, for these mixes, which were also observed to have the highest dynamic yield stress, and similar formulations additional precautions must be taken regarding the choice of the torque amplitude in order to avoid paste history effects and allow for comparisons to pastes of different viscosities at short rest times.

The second method of measurement tested, commonly known as constant rotational speed method, yielded interesting results as detailed in Fig. 4. However, as mentioned earlier, data collection was not possible at the age of 15 min due to a structural breakdown during the introduction of the paste into the rheometer. This implies that 15 min was not enough time for the paste to structurally build up before measuring. While the age and rest time played a role in the rise of the static yield stress, the chemical admixtures induced a significant increase in static yield stress for five mixtures (mix 4 and mixes 9 to 12) as shown in Fig. 4. A consistent difference between these five mixtures and others is the lack of accelerator which, decreases the yield stress. The ready-mix accelerator was designed to accelerate after a certain time to consider the transportation time. Comparisons between mix 4 and mixes 2 and 3, which have nanoclay (C) and viscosity modifying agent (VMA) alone, reveal that the observed trend is due to an interaction between the nanoclay and the viscosity modifying agent and not either of the admixtures alone. In contrast, mix 9, which contains only the C-S-H seeds (X), shows a similar increase in static yield stress to mixes 10 to 12 which include C-S-H seeds in combination with nanoclay and VMA. Therefore, combining these three chemical admixtures can help boost considerably the yield stress, particularly the C-S-H seeds and the VMA yielded the highest value of yield stress at 390 Pa in mix 10. This high value demonstrates capability of chemical admixtures to increase, in a short time, the structural build up which is defined by the structuration rate. As shown in Table 1, mix 10 has the highest structuration rate that is approximately constant about 8.75 Pa/min on average. The flocculation due to the nanoclay (C) and the C-S-H bridge formation are primarily responsible for the strong structural build up in these mixtures, as described in [15]. As explained above, the negative values of some of the structuration rate calculations can be explained by the influence of the rest time.

Comparing the two methods, the constant rotational speed method is best fit for these cement paste mixtures because of its low rotational speed. The paste is less disturbed by the measurement which enables quick structural recovery for the next measurement. Due to the thixotropic nature of cementitious materials, a measurement method which provides less disturbance to the paste is highly recommended by numerous authors [2, 13, 16]. However, this measurement method is not suitable for a more fluid paste. As the fluidity of these 16 mixtures varies with the chemical admixtures, other measurement methods need to be explored to enable broader research capability.

In the context of 3D printing, the same mixture must provide both strong static and dynamic yield stress. The effect of admixtures at a given age and temperature must fulfill this condition. For instance, as shown in Fig. 1, mix 12 at room temperature has the highest dynamic yield stress and the corresponding static yield stress (Fig. 3 and 4) at the same temperature are among the highest values. However, the time of the

measurements is different. While dynamic yield stress is a measurement of the resistance to flow for a paste in flow, the static yield stress depends on the structural build up with time of the paste at rest as measured by structuration rates [7]. From these identified mixtures, the measurements of the static yield stress enable the study of the effect of admixtures. Further formulation refinement is required to create a suitable region of overlap for the regions of high dynamic and high static yield stress to optimize a cement mixture for 3D printing.

5 Conclusion

The dynamic and static yield stresses have been explored to determine the effect of admixtures in cementitious materials. Calibration factors from a geometry system known as spindle geometry, suggested by NIST, were used with linear and nonlinear fitting to calculate both yield stresses. The dynamic and static yield stresses values vary with the chemical admixtures. A large increase was recorded over time for static yield stress measured by the constant rotational speed method for mixes without the selected accelerator. This accelerator will become more interesting in studies on the build-up rate and of longer duration. To calculate the structural breakdown, the constant rotational speed measurement method was the most suitable for this cement paste. An increase of dynamic yield stress and decrease of plastic viscosity was observed above a certain temperature showing the possibility to control pumpability and printability with temperature. These results show early age property methods are a promising method to formulate and test materials for 3D printing, which require a high capacity for rheological properties control. Further investigation considering temperature, structuration rate and other measurement methods such as small amplitude oscillatory shear (SAOS) method is needed.

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Penetration Study of Liquid in Powder Bed for 3D Powder-Bed Printing

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Abstract. Powder-bed 3D printing technology is attractive as it allows to build complex structures and optimize cost and time. The liquid is sprayed to bond the powder bed at pre-determined positions layer by layer. After print, the non-bonded particles are removed during post-processing. From a material point of view, it is crucial to understand the interactions between liquid and powder bed. Indeed, the spreading of water in the powder bed impacts the hardened performances of the printed elements. In the current work, we first measure the one-dimension water penetration over time for pure cement powder, pure plaster powder and a modified plaster powder suitable for 3D printing. We then show the hardened morphology of water penetrated and bonded area. Our results and analysis suggest that for common inorganic reactive powder, the penetration depth is higher than the one required to control the shape. Thus, it is necessary to modify transfer properties in order to control the liquid penetration depth. We furthermore identify key parameters to design applicable dry powder mixtures for 3D powder-bed printing technology.

Keywords: Powder bed · Cement · Plaster · Penetration · 3D printing

1 Introduction

In the field of digital fabrication with concrete, 3D printing concrete is known as one of the widely used and promising technology [1]. It can be classified as extrusion, formwork printing, temporary supports, slipforming and particle-bed printing [1], etc. Among those techniques, particle-bed printing is beneficial to fabricate free form members and reduce fabrication time. This construction technique adopts selective paste intrusion/activation or binder jetting to bond the particle bed layer by layer and the non-bonded particles are removed during post processing [2].

From a material point of view, the problems that particle-bed printing technique faces during processing lies in the interaction between binder and particle bed. This includes the penetration feasibility of binder into the particle bed, the precision of printed objects, the binder retention ability within porous particle network and

hydration bonding ability [2–5], etc. All those factors are closely relevant to the mechanical performance and durability of the printed structures and elements.

In the current work, we first measure the one-dimension water penetration over time for pure cement powder, pure plaster powder and a modified plaster powder suitable for 3D printing. We then show the hardened morphology of water penetrated and bonded area. Our results and analysis suggest that for common inorganic reactive powder, the penetration depth is higher than the one required to control the shape. Thus, it is necessary to modify transfer properties in order to control the liquid penetration depth. We furthermore identify key parameters to design applicable dry powder mixtures for 3D powder-bed printing technology based on the Washburn theory [6].

2 Materials and Methods

2.1 Materials

3 types of reactive powder were used in this study. They are CEM I Cement with a specific density of 3.15, pure plaster powder with a specific density of 2.63, and a 3D printing plaster powder (PXL Core Powder) obtained from the printer manufacturer (PXL Core, Z-Corp) with a specific density of 2.53. The Particle Size Distribution (PSD) of the powders were measured using a laser particle size analyzer (Malvern Mastersizer S) by dispersion the powders in isopropanol (Cf. Fig. 1). The median particle sizes of the cement powder, the pure plaster powder and the commercial plaster powder are around 11.5 μm , 12.5 μm and 35 μm , respectively. The main compositions of the 3D printing plaster powder are calcium sulfate hemihydrate (80%–90% by weight), vinyl polymer and carbohydrate.

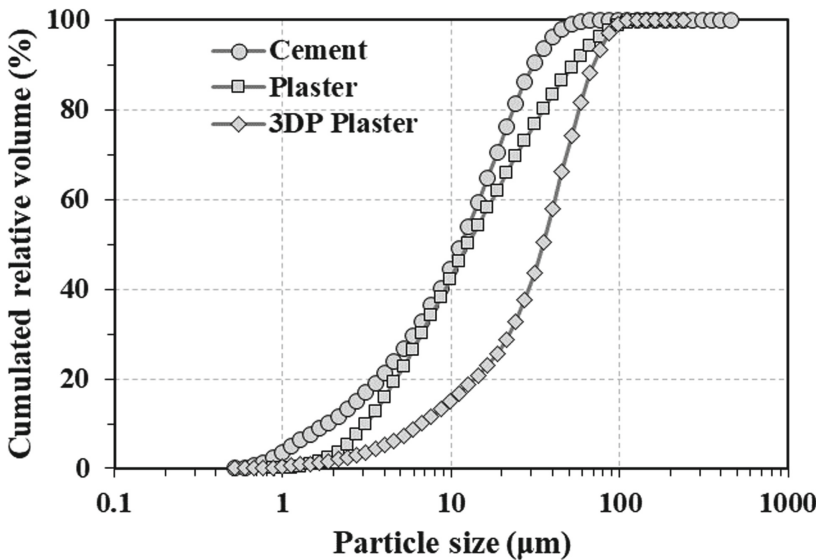
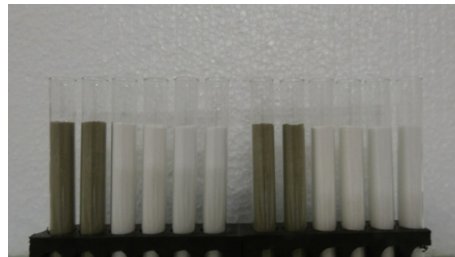


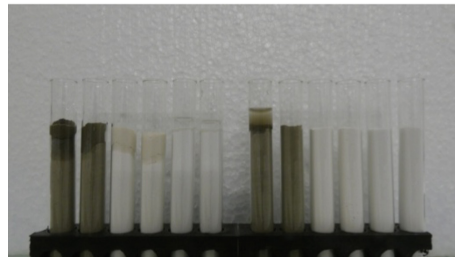
Fig. 1. Cumulative particle size distribution of the pure cement, pure plaster, and 3D printing plaster powders used in this study.

2.2 One-Dimensional Penetration Depth Measurement

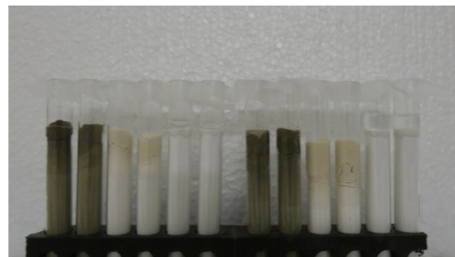
A one-dimensional penetration experiment was designed to characterize the penetration depth of different types of powder over time. Glass tube with an inner diameter of around 10.5 mm and a height of 10 cm was used in the measurement. The powders in the tube were gently vibrated to ensure of flat surface. The packing density of the three types of powder in the tube were measured before adding water on the top. They are 0.33, 0.33 and 0.42 for the pure cement powder, the pure plaster powder, and the 3D printing plaster powder, respectively. The surface of powder bed was then entirely covered by 0.4 ml and 0.8 ml distilled water and sealed by paraffin film to avoid evaporation (Cf. Fig. 2). It should be noted that the high amount of the liquid allows us to distinguish the different penetration depth of liquid in the glass tube for various powder mixtures. A digital camera was used to record the penetration depth of water over time. All the measurements were carried out at room temperature around 24 ± 2 °C. The penetration depth of liquid in each tube was then determined by averaging 3 measurements, i.e., left, middle, and right of each tube at each recording time.



(a)



(b)



(c)

Fig. 2. One-dimension measurement of water penetration in powder beds. (a) before adding water; (b) first tens of seconds upon contacting water; (c) water penetrated for 120 min.

2.3 Shape Characterization of Hardened Sample

The shape characterization of the hardened sample was carried out by dropping droplets on the flatly packed powder bed. An ultra-high performance pipettes with 1% precision were used to drop water onto the powder bed. The mass of each droplet is around 20 mg. 12–15 droplets of around 3.5 mm in diameter were dropped to the flat surface of the three types of powder beds. The spacing of the droplets was around 5–10 mm (Cf. Fig. 3). The sample was taken out by a sieve with mesh size of 200 μm after 12 h for pure cement powder and pure plaster powder, and 2 h for 3D printing plaster powder.

It should be noticed that in the current study, the penetration time of the droplets is within 10 min, whereas in this period, the water evaporation ratio is around 10% (data not shown here). It can be assumed that the influence of the drying phenomenon is neglectable in front of the final water penetrated region inside of the powder bed. Moreover, in practical powder-bed printing, deposited water “droplets” would be quickly covered by the next layer of dry powder. There can be a parallel effect of fresh dry upper material sucking water upwards, and at the same time preventing water evaporation (unlike the case presented in this paper).

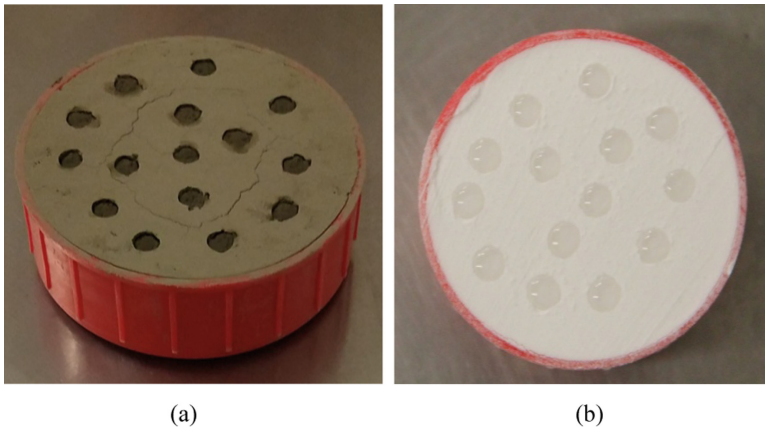


Fig. 3. The droplet morphology on powder bed.

3 Results

3.1 Penetration Depth Over Time

We plot in Fig. 4 the penetration depths of water in the pure cement powder, the pure plaster powder, and the 3D printing plaster powder over time. It should be first noted that for the penetration test with 0.4 ml liquid addition, the time interval between adjacent images is 15 s, whereas for the later penetration test with 0.8 ml liquid addition, a shorter time interval, 10 s, was chosen. It can be seen that for pure cement and pure plaster powders, the penetration depth of water increases extremely rapid

during the first several minutes. This leads to a large measurement uncertainty during first several minutes. Then the penetration velocity then decreases sharply and approaches to a plateau at the end of the testing time. And the penetration behavior over time follows the same manner for both types of the powder. However, in the case of the 3D printing plaster, the penetration depth is far lower than the other two types of powder.

Besides, in the case of pure cement and pure plaster powders, the penetration depth at the end of the testing time for the amount of 0.8 ml water initially added on the surface of the powder beds, is almost doubled compared to that of the 0.4 ml water. Nevertheless, in the case of the 3D printing plaster, the penetration depth is nearly the same in spite of different amount of water added on the top.

The very different penetration results between pure cement/plaster powder and the 3D printing powder indicates that the organic components added in the printing powder extremely increase the resistance for water to penetration.

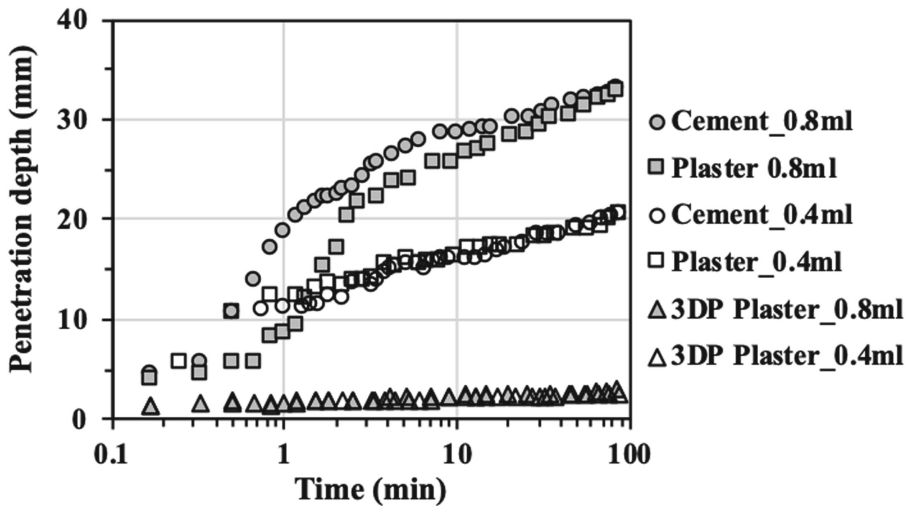


Fig. 4. Penetration depth of water in powder bed as a function of time.

3.2 Hardened Sample Morphology

We then show in Fig. 5 the morphology of the hardened granules that the droplets penetrate in for the three types of powder. The shape is close to irregular sphere with diameter around 5 mm for the granules that made up by pure cement powder and pure plaster powder. We moreover find that they are extremely fragile and very loosely structured. However, for the granules that made up by 3D printing plaster powder, the shape is far more regular and closer to a sturdy disc with a thickness around 2 mm and diameter of 5 to 8 mm. This indicates that it is difficult to control the penetration depth and shape for the conventional reactive mineral powders such as the pure cement and pure plaster powders studied here. In order to better control the shape of the liquid

propagation area, specific strategy is required to modify the powder components so that the penetration process can be well controlled over time.

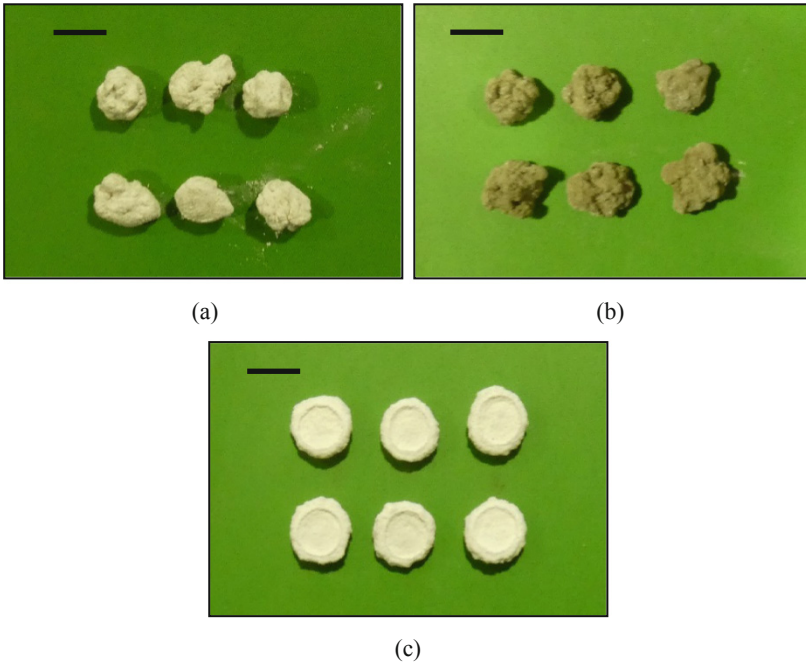


Fig. 5. The morphology of the droplet penetrated area after hardening (top view): (a) pure plaster powder; (b) pure cement powder; (c) 3D printing plaster. The length of the scale bar stands for 5 mm.

4 Analysis

According to the results obtained in Sect. 3, it can be deduced that the penetration consequences could strongly determine the printability of a certain type of powder in case of the 3D powder-bed printing technology.

As a well-known penetration theory, Washburn imbibition equation describes the penetration depth of a liquid with a pressure gradient dominated by the capillary pressure. For the porous media such as the powder stacks studied here, the water propagation length before fully consuming the free water above the surface of the powder bed, writes [6]:

$$H = \sqrt{\frac{k_0 P_{cap} t}{2\mu}} \quad (1)$$

where μ is the liquid viscosity; H the water penetration depth; t the time; k_0 the permeability which can be estimated by the Kozeny-Carman formula:

$$k_0 = \frac{\omega^3}{45(1-\omega)^2} r^2 \quad (2)$$

where ω is the porosity and r the pore radius [7, 8]; P_{cap} the capillary pressure which writes:

$$P_{cap} = \frac{\gamma}{r} \quad (3)$$

where γ is the surface tension of liquid.

It is seen from above equation that the penetration depth of water in the powder bed scales with the square root of time. Hereafter, in the case of desaturated condition, i.e. the water fully penetrates into the powder bed, the penetration depth is stated to be a power function of the saturation level and the velocity of the water propagation front is expected to decrease over time [9, 10].

Therefore, it is suggested that any approaches that could decrease the liquid propagation in the powder bed can be potentially applied for 3D powder-bed printing technology. First of all, as can be seen in $k_0 = \frac{\omega^3}{45(1-\omega)^2} r^2$ (2), the decrease in porosity is accompanied by a decrease in pore size, which is beneficial to the decrease of the penetration depth at certain time. Secondly, a decrease of surface tension is also expected to decrease the penetration depth. But this is limited due to the fact that this property can only be reduced to half of the pure water. Thirdly, an increase of the liquid viscosity is seen to be the most feasible method since this property can be increased to 2 to 3 orders of the pure water with the assistance of viscosity modify agents or also called thickeners. However, given sufficient amount of liquid, as long as the resistance cannot overcome the capillary suction, the penetration depth will keep increasing slowly. Hence, short setting time shall be preferred. It could be the reasons that by introducing viscosity modifying ingredients and reducing setting time, an extremely low penetration depth can achieve for the 3D printing plaster (Cf. Fig. 4).

We therefore suggest that the combination of the above proposed approaches will effectively guide the design of the realistic printing powders for the digital 3D printing powder-bed technology. To quantitatively predict the penetration behavior using the proposed theoretical frame, further investigations are required including characterization of the rheological properties of the fluid and of hydration kinetics of the system.

5 Conclusion

In the current work, we first showed the one-dimension water penetration consequence over time for pure cement powder, pure plaster powder and a type of modified plaster powder suitable for 3D printing. We then showed the hardened morphology of water penetrated and bonded area for the three types of powder. Our results and analysis suggest that for common inorganic reactive powder, the penetration depth is far higher

than it is required and it is necessary to modify the component properties in order to control the liquid penetration depth. We furthermore proposed some general ideas for designing applicable dry powder mixtures for 3D powder-bed printing technology based on the Washburn theory.

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Mechanical Performance



Quantitative Evaluation of Orientation of Steel Fibers in 3D-Printed Ultra-High Performance Concrete

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Abstract. Despite the growing interest in 3D concrete printing, the inset of tensile reinforcement poses severe limitation to the advancement of the technology. Inclusion of short steel fibers is a potential alternative to improve the tensile properties of 3D-printed concrete. In the extrusion-based printing process, steel fibers tend to align predominantly in the printing direction. However, currently there is no quantitative evaluation of the orientation of fibers in 3D-printed fiber-reinforced concrete. An experimental program was designed in this study to quantitatively investigate the fiber alignment in a non-proprietary 3D-printable ultra-high performance fiber-reinforced concrete (UHPFRC). Digital image analysis was performed on thin UHPFRC specimens to quantify the fiber orientation distribution. In addition, the effect of the fiber orientation on the mechanical response of the 3D-printed UHPFRC with 2% by volume of micro steel fibers was determined by means of three-point bending tests. Conventionally mold-cast UHPFRC specimens were also prepared and tested for comparison purposes. The results of the digital image analysis revealed an enhanced fiber alignment parallel to the printing direction in the 3D-printed specimens, which in turn significantly enhanced the flexural performance of the printed UHPFRC as compared to the mold-cast counterpart.

Keywords: UHPFRC · Steel fiber · Fiber orientation · 3D concrete printing · Mechanical properties · Image analysis

1 Introduction

Three-dimensional concrete printing (3DCP) has received increasing attention in recent years due to its potential for improvement in the construction speed and fabrication of complex geometrical structures without conventional formworks [1–3]. The structures are created by depositing the cementitious material in a layer-by-layer process by using a printing system [4].

The major challenges posed to the expansion of 3DCP are limitation of printable concretes and inclusion of conventional reinforcement [5]. Recently, the authors of this paper have developed an ultra-high performance fiber-reinforced concrete (UHPFRC) mixture for extrusion-based 3DCP applications [6, 7]. Short steel fibers were added to provide resistance against tensile stresses. During printing of the developed UHPFRC, it was noted that the steel fibers tend to align predominantly in the printing direction [7]. Similar observations were reported in previous studies on printable cement/geopolymer mixtures reinforced by steel/polymeric fibers [8–11]. However, currently there is no quantitative evaluation of the orientation of fibers in 3D-printed fiber-reinforced concrete.

In this study, an experimental program was designed to quantitatively investigate the fiber alignment in the 3D-printable UHPFRC. Digital image analysis was performed on thin cut sections to quantify the orientation of fiber reinforcement. In addition, the effect of the fiber orientation on the mechanical response of the 3D-printed UHPFRC with 2% by volume of micro steel fibers was determined using the three-point bending experiment. Conventionally mold-cast UHPFRC specimens of the same mixture were also prepared and tested for comparison.

2 Materials and Mix Design

The 3D-printable UHPFRC composite consisted of Type GP ordinary Portland cement (OPC), densified silica fume, silica sands, superplasticizer, viscosity modifier, steel fibers and water. OPC and silica fume conform to the requirements of AS 3972 and AS 3582, respectively. The cementitious binder is made of 70% OPC and 30% silica fume. Water-to-binder mass ratio was 0.16. Three types of graded silica sands (fine, medium, and coarse sand) were used. Fine-to-medium-to-coarse silica sand mass ratio was 4:3:3. The total sand-to-binder mass ratio was 1:1. A polycarboxylate ether-based superplasticizer at 1% mass ratio of the binder and nano-clay viscosity modifier at 0.3% mass ratio of binder were used as admixtures. Short brass coated steel fibers with the properties provided in Table 1 were used at a volume fraction of 2%.

Table 1. Properties of steel fibers

Length (mm)	Diameter (μm)	Density (g/cm^3)	Young's Modulus (GPa)	Strength (MPa)
6	200	7.85	200	2500

3 Experimental Process

3.1 Mixing, Printing, Casting, and Curing

Dry cementitious binder and the three sands were mixed for three minutes in a 60 L capacity planetary mixer. Three-quarters of the measured water was then added and mixed for five minutes. The superplasticizer was mixed with the remaining water and

added to the mixture. After achieving adequate fluid consistency, the steel fibers were gradually added and mixed for six additional minutes. In the final step, nano-clay was added to the mixture. Visual inspection confirmed uniform dispersion of the fibers.

A gantry type 3D printer with a printable volume of 1.8 m (L) $\times$ 1.6 m (W) 1.8 m (H) was used in the study. The cementitious composite was fed to the augur-type extruder of the printer. A circular nozzle with 30 mm diameter was fixed to the bottom of the extruder. The print speed was 30 mm/s and the extrusion rate was 1.3 L/min. Solid slabs measuring 270 mm (L) $\times$ 270 mm (W) $\times$ 60 mm (H) were 3D printed (See Fig. 1). Six layers, each with a height of 10 mm, were stacked upon one another in a designated printing path, as shown by the white arrows in Fig. 1. The fresh mixture was cast into 50 mm cube molds and 40 mm $\times$ 40 mm $\times$ 160 mm prismatic molds for the preparation of conventional mold-cast specimens.

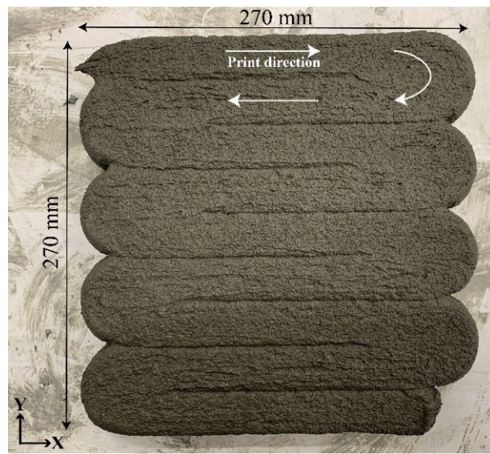


Fig. 1. 3D-printed solid slabs using the UHPFRC

Following the printing process, the printed slabs were fully covered with plastic sheets and cured at room temperature (23 ± 3 °C) for 48 h. Afterwards, the hardened slabs were steam cured at 90 °C for 48 h. The mold-cast specimens were demolded after 24 h and left at room temperature for additional 24 h prior to steam curing similar to the printed slabs. At the end of the steam curing regime, all specimens (mold-cast and printed) were left at room temperature for further 72 h. The total curing time adopted in this study was 7 days. After such accelerated curing, the authors observed no significant gain in strength beyond 7 days (up to 28 days). Similar observations were reported elsewhere [12, 13]. Therefore, all specimens were tested at the age of 7 days in this study.

3.2 Testing of Specimens

50 mm cubes and 50 mm $\times$ 50 mm $\times$ 200 mm prisms were sawn from the printed slabs for compressive and flexural strength tests, respectively. All sides of the sawn

specimens were then ground flat for smooth surface. Constant load control rate of 0.33 MPa/s was applied for compression loading. Displacement control rate of 1 mm/min was used to investigate flexural behavior under three-point loading. Loading directions are denoted in Fig. 2. The specimens were loaded in three test directions in compression (see Fig. 2a) and three test directions in flexure (see Fig. 2b and 2c). Six specimens were tested for each type and direction of loading. Same load and displacement control rates were used for testing the mold-cast specimens.

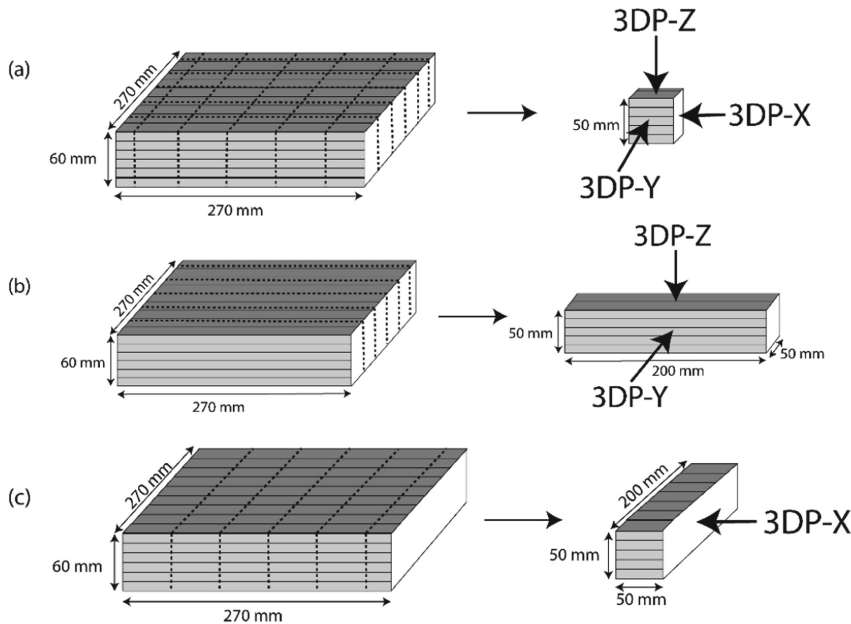


Fig. 2. Cutting diagrams and testing directions of 3D printed UHPFRC for (a): Compression testing, and (b) and (c): flexural testing

3.3 Fiber Orientation

The fiber orientation in the 3D-printed and mold-cast UHPFRC was quantified using an image processing technique [14, 15]. The printed and mold-cast specimens with cross-section of 50 mm × 50 mm were cut across the horizontal plane. Each specimen was cut to a thickness of 15 mm. All specimens were ground to achieve polished surfaces. A flatbed photo scanner (HP Scanjet G3110) was used to obtain high resolution images of the cut sections. The acquired RGB images were converted into grayscale images using an image analysis software. By selecting an appropriate color contrast threshold, these grayscale images were converted to binary images and the fiber orientation with respect to the printing direction was discretely measured. It should be noted that the selection of appropriate color threshold is quite user- and experience-dependent. In both mold-cast and printed samples, at least 300 steel fibers were identified and measured. Figure 3 shows the step-by-step process of image analysis adopted in this study.

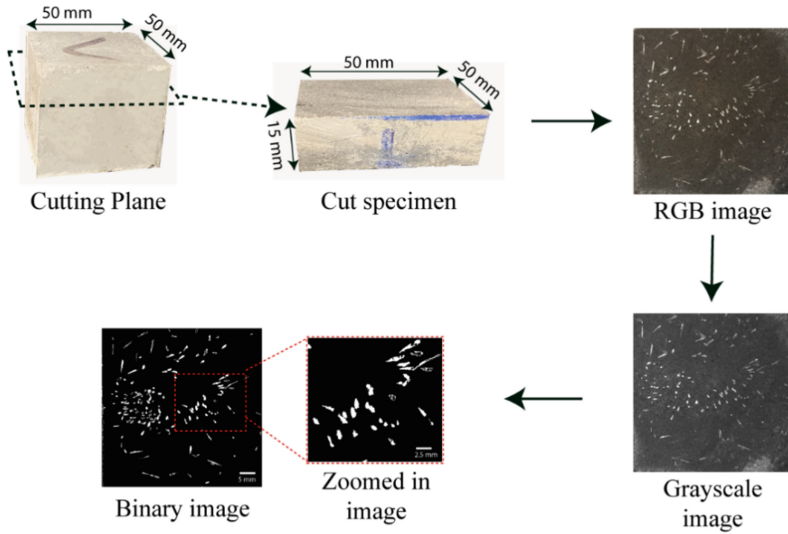


Fig. 3. Image processing technique to evaluate fiber orientation in UHPFRC

4 Results and Discussion

4.1 Compressive Strength

Anisotropic behavior was observed in the compressive strength of the printed specimens depending on the loading direction (See Fig. 4). The highest compressive strength was observed in the printing direction (3DP-X) due to the compaction in this direction during the extrusion process. In the other two directions (Y and Z), the compressive strength was lower than that in the X direction. Similar anisotropic observations have been reported in previous studies for different printable building materials [16, 17]. The mean compressive strength of the mold-cast specimens was similar to that of the strength achieved in the printing direction of the printed specimens.

4.2 Fiber Orientation

The frequency distributions of fiber orientation in the printed and the mold-cast specimens are shown in Fig. 5. The fiber orientations of 0° and 90° represent the directions parallel and perpendicular to the printing direction (X direction). In the printed specimens the frequencies of lower degrees of fiber orientations ($<20^\circ$) were significantly higher than the corresponding frequencies in the mold-cast specimens, indicating fiber alignment parallel to the printing direction in the printed specimens. Figure 6 shows a Gaussian (normal) probability density function (PDF) fit for the

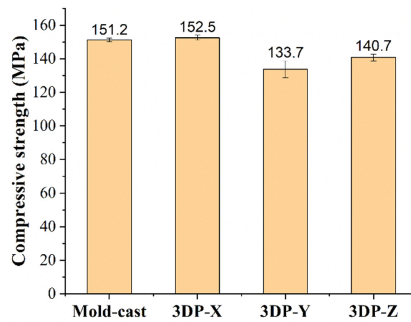


Fig. 4. Mean compressive strength of UHPFRC

observed fiber orientation distributions of the printed and mold-cast UHPFRC specimens. The area under the PDF between a particular range of orientation angles gives the probability of fibers aligned in that range of orientation angles. The expected value of the PDF of the printed specimens was 22° with respect to the printing direction, while that for the mold-cast specimens was 41° .

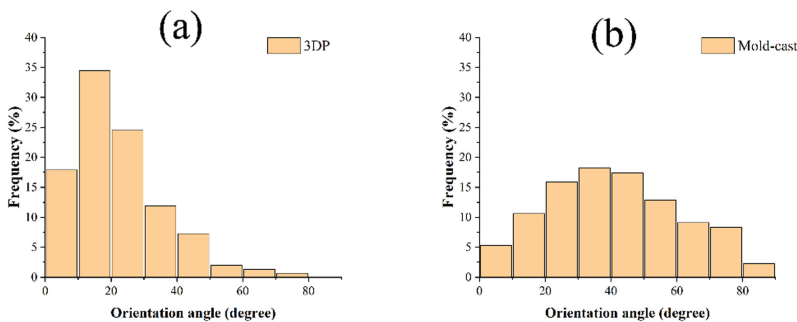


Fig. 5. Frequency distribution of fiber orientation in UHPFRC for (a): 3D printed specimens, and (b): mold-cast specimens

4.3 Flexural Strength

The mean modulus of rupture (MOR) of the mold-cast and printed UHPFRC specimens are shown in Fig. 7. Similar to the compressive strength results (see Fig. 4), an anisotropic behavior was observed in the MOR. In the printed specimens, the highest MOR was observed when the forces were applied on the specimens in Z direction, followed by Y and X directions. The higher MOR in 3DP-Z and 3DP-Y specimens indicates greater alignment of fibers in the printing direction. The MORs of these specimens were also greater than that of the mold-cast specimens with lesser preferential fiber alignment. The flexural strength results are in good agreement with the fiber orientation results. The higher MOR of 3DP-Z specimens than 3DP-Y specimens can

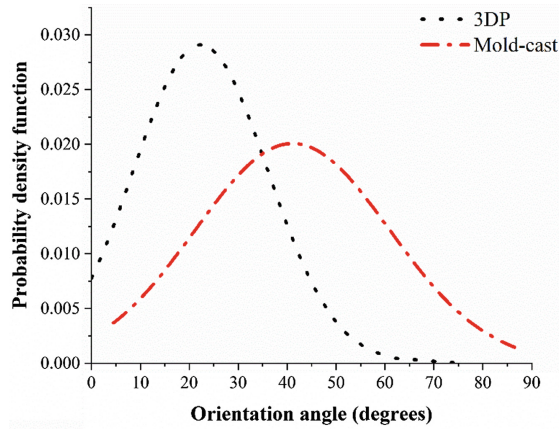


Fig. 6. Probability density function of fiber orientation in UHPFRC

be attributed to the self-weight of the specimens in Z direction, causing compaction of the bottom layers that resist the tensile stresses. In 3DP-X specimens, the loading direction was parallel to the layer interfaces, which are the weakest planes in the printed specimens. This resulted in the lowest MOR in X direction.

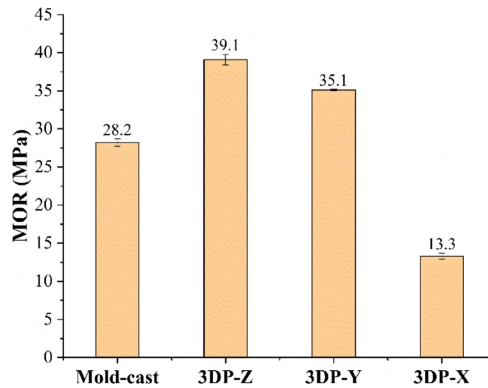


Fig. 7. Modulus of rupture of UHPFRC

5 Conclusions

The alignment of fibers in a UHPFRC due to extrusion-based 3D-printing process was quantitatively analyzed in this study. A 3D-printable UHPFRC with 2% volumetric addition of steel fibers was used in this study. The effect of fiber orientation on the mechanical properties was also studied. The following conclusions are drawn:

- (1) Extrusion-based 3D-printing process resulted in greater alignment of short steel fibers along the printing direction as compared to the conventional mold-casting method. Using digital image and statistical analyses, the expected value of fiber orientation in the printed specimens was 22° as compared to 41° in the mold-cast specimens.
- (2) The fiber alignment along the printing direction considerably improved the MOR of the printed specimens in 3DP-Z and 3DP-Y directions as compared to that of the mold-cast specimens. The MOR in 3DP-X direction (parallel to interfaces between layers) was lower than that of the mold-cast specimens.
- (3) Anisotropic behavior was observed in the printed specimens under compression. Among the printed specimens, the highest compressive strength was observed in the direction of printing (3DP-X). The strength of the 3DP-X specimens was comparable to that of the mold-cast specimens.

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Steel Fiber Links in 3D Printed Concrete

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Abstract. 3D concrete printing exhibits the potential to proliferate the industrialization of the concrete construction sector, which is notoriously conservative and indolent towards change. This emerging technology is propitious given its advancements in geometric design freedom, reductions in construction time, waste and material usage through formwork-free construction. However, when 3D concrete printing is fastidiously compared to current methods of concrete construction, a detrimental disadvantage, the absence of effective steel reinforcement is evident. Therefore, the amelioration of the brittle interlayer interface is the focus of several 3DCP research and industry endeavors. Steel reinforcement is favored as most modern concrete structures rely on the compressive and tensile strength of concrete and steel, respectively. However, a significant technical challenge is posed by the addition of reinforcement during the automated 3DCP process. Thus, the post-crack behavior of specimens reinforced during the printing process with straight steel fibers orthogonal to the interlayer interface is experimentally evaluated through four-point flexural tests in this research. The brittle interfacial failure is ameliorated through the addition of steel fibers that link consecutively deposited layers.

Keywords: 3D concrete printing · Steel fiber reinforcement · Interlayer bond strength · Experimental testing · Mechanical performance

1 Introduction

Concrete is volumetrically the most far-reaching human-made construction material across the globe. There are a plethora of advantages to utilizing concrete for infrastructure construction. However, due to the continued growth in the global population and imminent climate change, structural engineers are faced with contemporary challenges to provide sustainable infrastructure at an accelerated rate. Therefore, a demonstrable need for unconventional construction methods that ameliorate the inadequacies of conventional construction is evident.

Consequently, there is tremendous interest in construction methods such as 3D concrete printing (3DCP). 3DPC promises to provide more sustainable, flexible and affordable infrastructure at an industrialized rate during the nascency of the digital construction epoch. However, despite these foreseen advantages, 3DCP is still an emerging technology that is plagued with numerous technical challenges. These challenges include limited material development to date, active control of rheological

properties during the printing process, code-compliant durability and mechanical performance of printed elements, scalability of the printing process, and effective integration of reinforcement [1].

When 3DCP is meticulously juxtaposed with conventional methods of construction, the absence of effective reinforcing techniques is evident. This absence presents a salient difficulty for the widespread adoption of 3DCP as the interaction between concrete and steel is utilized by most concrete structures. However, if 3DCP is to industrialize the construction industry, the development of reinforcing techniques is constrained by its embodied automation. Thus, reinforcing techniques that form part of the automated printing process are favored to maximize the potential of 3DCP, and laborious interventions that vitiate automation should be avoided. Therefore in this research, the response of straight steel fibers that link subsequently deposited layers, bridging the interlayer interface, and can be incorporated during the automated process is experimentally evaluated through four-point flexural tests.

2 Interlayer Interface and Reinforcement

The orthotropic behavior of 3D printed elements is well documented in the literature. This behavior is caused by the inconstant layer and interlayer interface strength but less pronounced when printed elements are subjected to compressive stress than tensile stress [2, 3]. This strength differential is attributed to the brittle nature of the interlayer interface. Thus various experimental studies have been conducted to determine a suitable method to ameliorate the interlayer tensile behavior, including layer interlocking [4] and characterization of the print speed, nozzle standoff distance, and the print time interval influence [5]. These methods improve the tensile response of the interface only through adaptation of the printing process. Thus, the maximum tensile strength is limited to the tensile strength of the bulk material, in essence, the layers.

As a result, recent research and industry endeavors are focused on providing ductility to printed elements through the addition of reinforcement before, during printing, and after printing. A method to provide orthogonal and longitudinal reinforcement before printing is presented by Chinese construction company HuaShang Tengda Ltd [6]. Through their technique, reinforcement is installed prior to printing and then covered on either side by layerwise deposition using a specialized nozzle. Vertically ascending elements are constructed efficiently using this technique. However, construction automation and the construction of non-rectilinear elements are limited by its implementation; therefore, comprising the embodied advantages associated with 3DCP.

Three methods that incorporate reinforcement during the 3DCP process are reported in the literature. Firstly, fibers are entrained for an improved tensile capacity of printable concrete. Microfibers, made of basalt, carbon [3] and glass [2] are typically added in the mixing phase, while less workable short steel fibers are entrained during printing through sophisticated mechanisms [7]. However, the effectiveness of this technique is limited since entrained fibers are longitudinally aligned and seldom bridge the interlayer interface. Secondly, longitudinal entrainment of continuous steel cable at the nozzle is a widespread technique within the 3DCP industry [8–10]. However, it is

used in conjunction with laborious post-tensioning orthogonal to the interlayer interface. Lastly, the use of mesh or needle reinforcement is reported by Marchment et al. [11] and Roske et al. [12]. For mesh reinforcement, increased flexural strength, in addition to steel yielding followed by fracture, is reported. The steel is reported to yield rather than debond from the printed matrix when the mesh is incorporated. The composite flexural or tensile strength of needle reinforcement, short orthogonal steel bars embedded in printed elements are not published to date. Although the development of a sophisticated nozzle or mechanism is required for these techniques, respectively, they are advantageously incorporated during the printing process.

Currently, most large-scale printed elements are reinforced after printing. Through this technique, the printed shell is used as permanent formwork with a conventional reinforced poured concrete core [11]. Notwithstanding the practical and widespread use of this technique, the potential for construction automation provided by 3DCP is hindered by the laborious installation of reinforcement and concrete pouring. However, it provides a stepping stone for the development and adoption of 3DCP within the concrete construction industry.

3 Experimental Study

The main objective of the experimental research is to evaluate the effect of steel fiber reinforcement orthogonal to the interlayer interface of 3D concrete printed specimens.

Thus, four-point flexure is chosen to enable the evaluation of interlayer rupture and post-peak behavior. Flexural tests embedded on orthogonally reinforced and unreinforced specimens with the applied load parallel to the interlayer interface. For further comparison, tests are also performed on unreinforced specimens with the applied load perpendicular to the interlayer interfaces. The tests are performed on five specimens per category at seven and 28-day curing ages, as presented by the experimental program summary in Table 1.

Table 1. Experimental program

Curing age	7-day		28-day			
Load direction*						⊥
Number of fibers	0	2	0	1	2	0
Number of specimens	5	5	5	5	5	5

(*⊥ perpendicular to the interlayer interface; || parallel to the interlayer interface)

3.1 Specimen Preparation and Materials

Four 650 × 650 × 200 mm (L × W × H) square hollow sections are printed at 60 mm/s in a laboratory size gantry 3D concrete printer at the Building Materials and Structure Laboratory, located in the Division of Structural Engineering and Civil

Engineering Informatics at Stellenbosch University. The printer is equipped with a 25 mm circular nozzle, and a 10 mm layer height is prescribed. Therefore, the total print path length is 52 m, 2.6 m per layer, which yields a 43.33 s print time interval. More detail of the three degrees of freedom printer is provided by Bester et al. [13]. A fiber-reinforced high-performance printable concrete (FRPC), with a 0.45 water to cement ratio and 77.9 MPa 28-day compressive strength, containing 6 mm high modulus polypropylene entrained fiber is used for printing. The mix constituents are presented in Table 2. Prior to printing, an 80-liter equivalent dry mix is subdivided into 20-liter dry batches to ensure consistent material behavior during the printing of the four separate square hollow sections.

Table 2. FRPC mixture constituents and quantities.

Constituent	Description	kg
Cement	PPC Suretech CEM 11/A-S 52.5 N	562
Fly Ash	Durapozz Fly Ash (Class F)	162
Silica Fume	FerroAtlantica micro silica fume	81
Fine Aggregate	Malmesbury coarse sand	1144
Water	Potable tap water	256
Superplasticizer	Cryso Prima 310	4.9
VMA	Cryso Quad 20	2.4
Polypropylene fibers	6 mm High Modulus PP Microfibers	9

The sections are printed and subsequently cured in a 23 °C climate control room with a 65% relative humidity. During the printing process, DRAMIX 3D 65/60 GB steel fibers are consecutively inserted perpendicular to the interlayer interface, Fig. 1a, on the fifth, ninth, thirteenth, seventeenth, and twentieth layer, without interruption of the printing process, to form a continuous line of fibers with a 10 mm overlap. Note the manufactured length and diameter of these hooked end steel fibers are 60 mm and 0.9 mm, respectively. However, the 5 mm hooked ends are removed, yielding a 50 mm straight steel fiber. The hooked ends are removed to avoid cavity formation during insertion, which is caused by a combination of the maximum 4.75 mm aggregate size and the thixotropy of the FRPC, as comparatively illustrated in Fig. 1b. Furthermore, the fibers are inserted on the centroid of the square hollow sections to ensure efficient saw cutting a 40 mm height before testing. A specialized jig is manufactured to ensure parallel saw cut faces and consistent specimen dimensions.

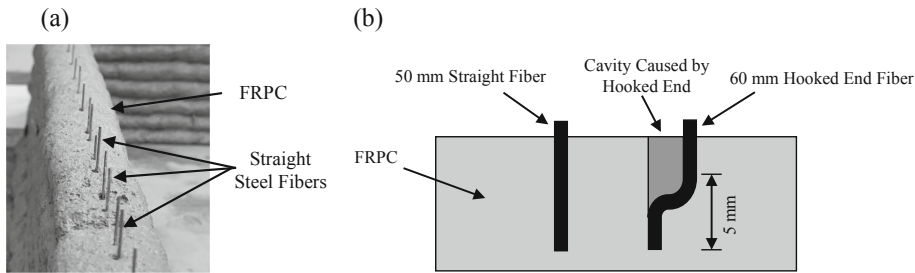


Fig. 1. Orthogonal steel fiber reinforcement in FRPC (a) fibers inserted during 3DCP; (b) schematized comparison of straight and hooked end fibers in FRPC.

3.2 Experimental Test Setup for Flexure Response

The flexural strength of $160 \times 37 \pm 2 \times 40$ mm (L $\times$ W $\times$ H) prisms are determined through four-point flexural testing, in accordance with EN 196-1 [14]. Note, the specimen width is dictated by the layer width, which exceeds the nozzle diameter of 25 mm. Moreover, the nozzle diameter is surpassed by the layer width because the chosen layer height is less than the nozzle diameter. Therefore, squeeze flow, also known as layer pressing, is induced to increase the interlayer bond strength at the expense of surface quality [15]. The tests are performed at a 0.25 mm/min crosshead displacement rate to 2.5 mm of total displacement in a Zwick Z250 material testing machine to capture the elastic and post-crack behavior of the specimens, using the four-point flexure test setup presented in Fig. 2a and 2b.

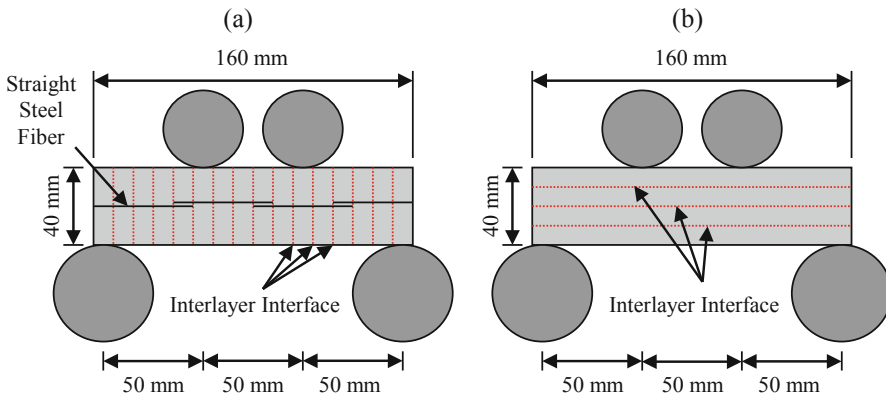


Fig. 2. Four-point flexural test schematic (a) printed specimen reinforced with steel fiber orthogonal to the interlayer interface and a parallel applied load; (b) printed specimen containing zero steel fibers with a perpendicular applied load.

4 Results and Discussion

The average ultimate load (F_u), displacement at ultimate (δ_u), modulus of rupture (f_r), its coefficient of variance, and post-peak behavior of the flexural tests are summarized in Table 3. The modulus of rupture is determined using Eq. (1) with the measured height (h), width (b), and ultimate load of the individual specimens, in addition to the total length (L) of 150 mm between the outer rollers, as illustrated in Fig. 2.

$$f_r = \frac{F_u \cdot L}{b \cdot h^2} \quad (1)$$

Brittle failure is observed in the seven and 28-day unreinforced specimens with the applied load parallel to the interlayer interface, named 7D0F||L and 28D0F||L, respectively. The point of failure is indicated with a dot in Fig. 3b and no post-peak data could be recorded despite a sampling rate of 50 Hz. Whereas, post-peak response and softening residual strength is observed in all the other specimens following the ultimate load. Moreover, interfacial fracture at similar flexural stresses is observed in all the specimens loaded parallel to the interlayer interface, irrespective of the curing age. Therefore, it is postulated that the interlayer bond strength starts to plateau after seven days of printing for the material tested in this research. However, further experimental research at one, seven, and 28-day curing ages should be conducted to validate this postulation. Due to the plethora of factors that affect the strength of the interlayer interface, a significant COV is produced by the specimens loaded parallel to it. The highest modulus of rupture is presented by the specimens loaded perpendicular to the interlayer interface. This result is expected since the modulus of rupture of these specimens is dominated by the layer, matrix, strength and not the weaker interfacial strength. Therefore, it is recommended to design and print concrete structures with the dominant action perpendicular to the interlayer interface. Nevertheless, a trend of increased flexural resistance by reinforcement across the interfaces is observed, together with residual flexural resistance during gradual pull-out of the steel fiber(s) bridging the interface.

Table 3. Results of four-point flexural tests.

Name	F_u [N]	δ_u [mm]	f_r [MPa]	COV [%]	Post peak behavior
7D0F L	786	0.106	1.94	20.07	Brittle
7D2F L	796	0.085	1.96	13.47	Softening
28D0F L	787	0.098	1.92	13.87	Brittle
28D1F L	915	0.110	1.96	21.59	Softening
28D2F L	717	0.099	2.03	14.61	Softening
28D0F⊥L	1750	0.155	4.47	13.11	Softening

Curves are fitted to the experimental force-displacement data of the specimen categories to enable effective juxtaposition of the post-peak behavior, as illustrated by

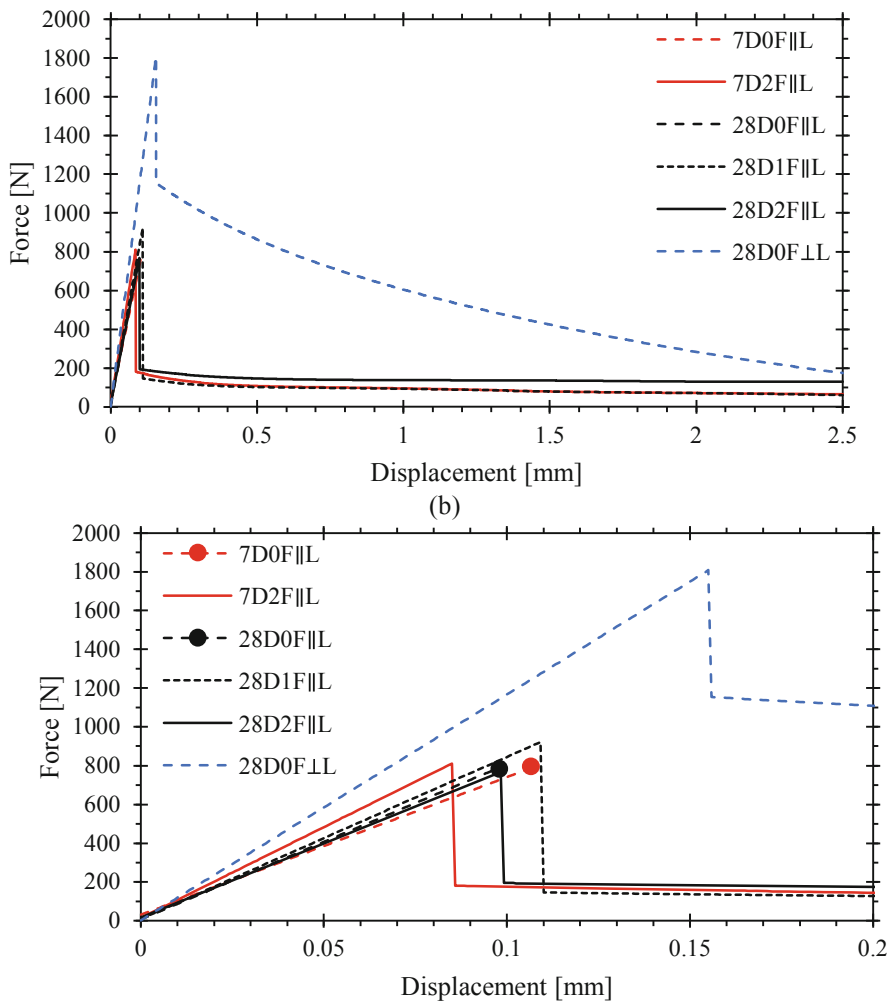


Fig. 3. Average force-displacement results of four-point flexure tests (a) softening behavior over the entire test range; (b) comparative peak force-displacement behavior.

Fig. 3a. Strong post-crack softening behavior is dominant in the specimens loaded parallel to the interface, which is expected from straight steel fiber reinforcement and aligns with results reported by Bos et al. [7]. However, a less noticeable difference between the fracture and post-crack force is observed in the specimens loaded perpendicular to the interface. This difference is attributed to the pullout capacity and strength of the high modulus polypropylene fibers entrained in the FRPC. Moreover, a stronger bond between the polypropylene fibers and the cementitious matrix is expected since they are incorporated during the mixing phase while the steel fibers are inserted during printing. The development of voids or insufficient contact between the cementitious matrix and the fiber is more likely to occur with the inserted fibers than

the entrained fibers. However, ductility is observed after crack development through the interface, as opposed to brittle failure of the specimens without steel fibers linking the layers.

The aforementioned post-crack behavior is provided by frictional pull out of the orthogonal steel fibers that decays as the imbedded length is reduced. A marginal increase in post-crack resistance is provided by the specimens which contain two fibers (28D2F||L) when compared with the single fiber specimens (28D1F||L), as illustrated by the higher force post-crack in Fig. 3a. Therefore, increased resistance can be provided by the addition of several fibers that bridge the interface. Furthermore, post-crack flexural resistance should increase if fibers are strategically inserted further from the centroid. A similar elastic response and average displacement at the ultimate load of 0.102 mm are observed in all the 28-day specimens loaded parallel to the interface, as illustrated in Fig. 3b. However, a 150% increase in displacement before the onset of fracture is observed when compared to the specimens loaded perpendicular to the interlayer interface.

5 Conclusion

The brittle interfacial behavior of 3DPC elements is a significant challenge that is the focus of research and industry endeavors. In this research, the behavior of straight steel fibers that orthogonally bridge the interlayer interface is evaluated through four-point flexural tests. The addition of orthogonal links is proven effective in providing ductile post-crack softening behavior under flexural load parallel to the interlayer interface. However, the flexural capacity of specimens loaded parallel to the interlayer interface is exceeded by that of perpendicularly loaded FRPC specimens. Therefore, the addition of more orthogonal straight links or hooked end fibers in conjunction with a specialized mechanism that prevents cavity formation during insertion through agitation of the thixotropic cementitious material is recommended for further research endeavors.

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Mechanical Characterization of Cement-Based Mortar Used in 3DCP Including Early-Age Creep Effects

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Abstract. Digital fabrication techniques combined with suitable cementitious materials have successfully led to the implementation of innovative manufacturing processes for concrete-like products. However, although significant advantages are expected in layered extrusion (LE) concrete technology, manifold engineering challenges arise from the process itself, such as the full control of the mechanical properties evolution during printing. Primarily, printed materials should satisfy specific early-age mechanical and rheological requirements, whose definition remains unstandardized. Additionally, scarce literature on testing procedures for early-age printable mortars is currently available. In this paper, uniaxial compressive tests are performed on cylindrical samples to determine the time-dependent compressive behavior and the early-age creep effects on fresh concrete. The load application conditions are varied in the experimental campaign in order to propose a proper mechanical characterization procedure for 3D printable cementitious mortars. Finally, results are implemented in an analytical model to predict the accumulated creep strain during the printing process. The outcomes highlight the role of the early-age creep in the development of global deformations.

Keywords: 3D concrete printing · Buildability · Uniaxial compressive tests · Early-age creep tests · Early age properties

1 Introduction

Today, digital fabrication (DF) with concrete is emerging as a set of promising technologies able to accurately recreate structural elements without formworks, while, at the same time, contributing towards advancements in construction cost management, safety and sustainability [1–3]. Focusing on the layered extrusion manufacturing process (e.g., contour crafting [4], 3D concrete printing [5]), an automated printing apparatus typically extrudes in layers a thixotropic cementitious mixture, following a digitalized path subdivided into slices. Related engineering challenges originated by such a digitalized manufacturing process are manifold, and the primary requirements of cementitious materials for layered extrusion can be summarized as follows:

- **Pumpability**, describes the ease by which the fresh mix is transported from the pump to the extrusion nozzle [6];
- **Extrudability**, is the ability to extrude the mix throughout a nozzle without considerable cross-sectional deformation and with acceptable degree of splitting/tearing of filament [6];
- **Buildability**, is the ability of an extruded material to retain its geometry (shape and size) under sustained and increasing loads [7].

In this framework, design and control the printing technique primarily resides in optimizing the concrete compatibility with the printing system; specific rheological properties are required for concrete to be printed (pumpability and extrudability requirements), whereas the physical-mechanical properties are important for buildability and filament shape retention after extrusion [8]. Since no rigid mould participates in the construction process, high compressive strength and high stiffness is required: after fresh material deposition, each concrete layer must be able to carry its self-weight and the weight of the layers above it. With a specific emphasis on buildability, it clearly appears that an adequate knowledge on the compressive behaviour of printable materials in early age state is required. In particular, knowledge on the time evolution of the constitutive behaviour of concrete under compression [9] is essential to predict the stress/strain state of each layer and to ensure the stability of the whole element during the printing process.

Moreover, 3D printable concrete is generally characterized by a high paste volume, a low water-to-cement ratio (w/c), a high dosage of mineral additions and superplasticizer. Such peculiarities affect viscoelastic properties of concretes: on one hand, low water-to-cement ratios conduct to a higher strength; on the other hand, high paste volumes are more sensitive to creep and shrinkage [10]. Since the degree of hydration strongly influences the early age creep [11], higher creep strains are experienced if concrete is demoulded and loaded at ages inferior to 1 day [12–14]. As a consequence, to guarantee the dimensional control and to avoid stability problems during the printing process, a comprehensive insight on the early age compressive behaviour of 3D printable admixtures is necessary. Unfortunately, until now, compressive tests have no standard procedures for early age printable concrete samples. For instance, since the compressive strength and stiffness of early-age concrete inevitably changes during the printing process, each layer behaves differently, especially for high-value cycle-times (i.e., the time required to complete one build layer) [6].

As a result, uniaxial compression tests (UCTs) are performed in order to define the evolution over time of the corresponding constitutive stress-strain laws. Furthermore, at fresh state, even the development of strain under constant load is experimentally measured: authors refer to such viscoelastic effect as early-age creep. Both compression and early-age creep tests are executed at distinct concrete ages ($t = 0, 15, 30$ and 60 min). The authors have adopted the same testing procedure implemented in [15].

2 Materials and Methods

2.1 Material and Specimen Preparation

This section provides details of the concrete 3D printable mortar adopted as the reference mix in this research (already used in Asprone et al. [16] to fabricate reinforced concrete members based on a 3D concrete printing technology). The reference mix contains sand, with a maximum particle size of 4 mm, in agreement with the diameter of the nozzle used in [16] (25 mm). Polypropylene short fibres with a weight of 0.5% are also dispersed into the mixture to prevent plastic shrinkage-cracking during the early age curing stage and after the deposition process. As the viscosity of the printing material may be affected by the presence of fibres and by the low water/cement ratio ($w/c = 0.39$), the mix is adjusted by adding a polycarboxylate superplasticizer (SP = 0.10% in weight of cement) in order to achieve an optimal rheological balance with respect to material pumpability. The slump class of the concrete (S1) is evaluated according to the EN 12350-2:2009 procedure [17], while the average cubic strength ($R_{cm} = 53.5$ MPa) and the average cylindrical strength ($f_{cm} = 44.4$ MPa) are determined according to [18, 19].

Early-age compression and creep tests are performed on cylindrical samples with a diameter (d) of 60 mm and height (h) of 120 mm. This geometry is selected to exclude size effects due to particle size distribution and to obtain the aspect ratio $h/d=2$, allowing for diagonal shear failure. The fine aggregate is initially mixed for 60 s at low speed (140 rpm). Subsequently, such dry components are mixed with polypropylene fibres (140 rpm – 30 s). Water is then added, mixing again for 60 s (140 rpm). Finally, a poly-carboxylic SP (CE) is added gradually, mixing for 120 s at high speed (285 rpm). A plastic 3D-printed openable mould (see Fig. 1) is designed to reproduce cylindrical specimens with good shape retention. Improvements in sample preparation are achieved by using an internal nylon membrane (interposed between the mould and the lateral surface of the specimen) that effectively reduce the interface friction.

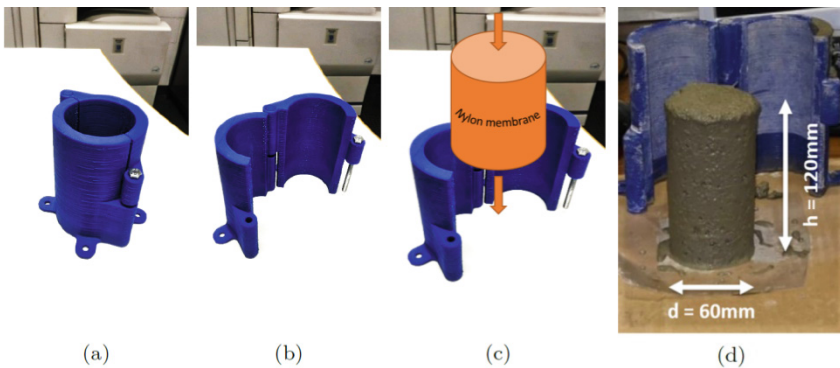


Fig. 1. 3D-printed openable mould: (a) closed, (b) open, (c) positioning of the nylon membrane, (d) example of a prepared sample.

2.2 Experimental Program

Cylindrical specimens are tested by means of an MTS electromechanical Universal Testing Machine, with a 10 kN capacity in a displacement-control condition at room temperature, $T \approx 22^\circ\text{C}$, and controlled relative humidity, $RH \approx 60\%$. Since no physical measurement on the sample is possible without altering it (e.g., attaching extensometer or strain gauges), stresses and strains are deduced from force-displacement data obtained from the testing machine. In order to achieve the time-dependent evolution of mechanical properties during printing, tests are carried out at distinct concrete ages of $t = 0, 15, 30$ and 60 min, with a displacement rate of 3 mm/min .

2.3 Uniaxial Compression Test

Tests are performed up to a vertical strain of 12% , i.e. 15 mm displacement. In order to eliminate any disturbance at the beginning of the test, authors have applied a pre-load of 2 kPa on each sample of the series. Results are then used to determine stress-strain relationships at different concrete ages, providing the evolution over time of the compressive strength $\sigma_{c,\max}(t)$ and the Young's Modulus $E(t)$. In particular, the stress is computed by dividing the recorded load for the cross-sectional area of the sample (i.e. 2826 mm^2), the strain is obtained by dividing the displacement of the loading head for the initial height of the sample. Improvements in stress calculation may be achieved by using a continuously updated section area; however, for the creep test the stress steps are small enough to avoid excessive enlargement of the cross-section. The Young's modulus is determined as the secant modulus from 0% to 2% of the strain. The continuous time-variation compressive strength and stiffness laws are obtained through a linear regression of the data related to each tested sample series.

2.4 Early-Age Creep Test

Tests are executed by applying displacements of the loading head up to achieve 8 N of vertical force reaction, i.e., the self-weight of the specimen, in order to simulate the above layer stacking (Fig. 2).

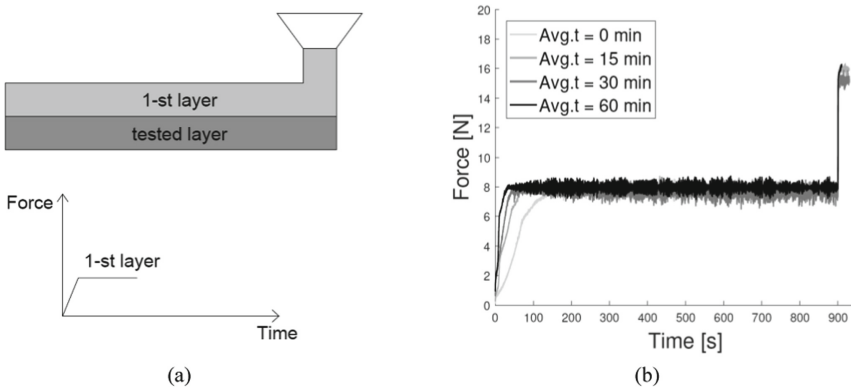


Fig. 2. Creep tests: (a) sketch of the testing protocol and (b) recorded load application.

Once such threshold is reached, the creep evolution is recorded under constant load. The global testing time for each concrete age ($t = 0, 15, 30$ and 60 min) is 900 s (including the time to reach the 8 N plateau).

3 Experimental Results

Figure 3 shows the experimental force-displacement curves for the reference concrete mix (with five individual specimens), while Fig. 4 displays the corresponding comparison between the average stress-strain curves related to distinct concrete ages. The compressive stress reaches the peak value (i.e. compressive strength $\sigma_{c,max}$) after an initial linear-elastic behaviour (the strain limit of the elastic range is approximately 2% for all the concrete ages), and then decrease again along the softening branch. There is a transition from plastic to brittle behaviour as the resting time increases, also visible in lateral deformations at failure. The curing time clearly increases strength and stiffness values: the material not only become stronger (higher yield stress), but also more rigid (higher elastic modulus). The augmented macroscopic elastic modulus and yield stress develop from an increase in the size and number of hydrate-bridges between the percolated cement particles. This phase is referred to as structuration [14]. The linear fit relationships of the compressive strength and Young's Modulus are plotted in Fig. 5.

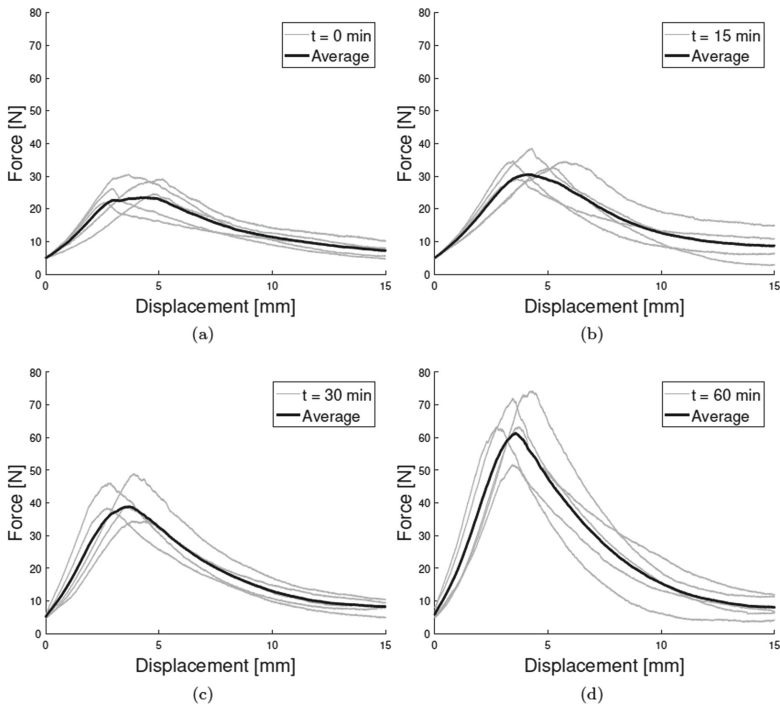


Fig. 3. Compression tests: average and individual results at different times - (a) 0 min, (b) 15 min, (c) 30 min, (d) 60 min.

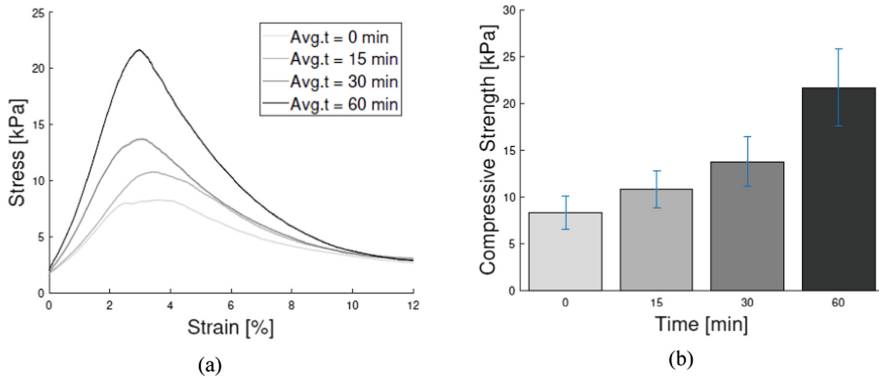


Fig. 4. Compression tests: average comparison - (a) stress-strain curves & (b) compressive strength with the standard deviation.

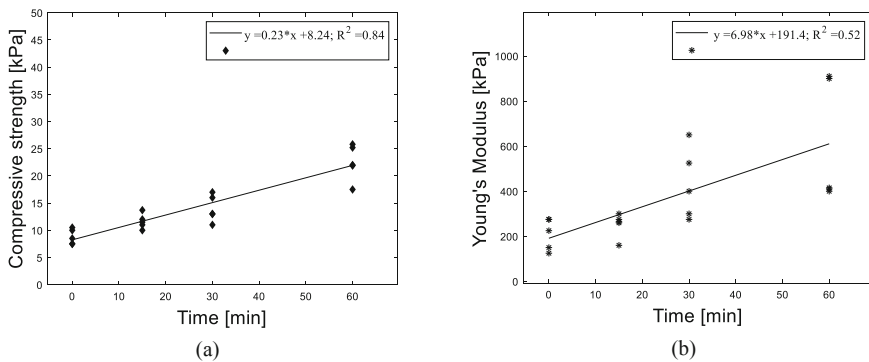


Fig. 5. Evolution over time of the compressive strength (a) and Young's modulus (b).

In detail, the average compressive strength is 8.24 kPa at 0 min, rising to 22.04 kPa at 60 min; meanwhile, the Young's modulus increases from 191.4 kPa at 0 min to 610 kPa at 60 min. The overall percentage increases with respect to the concrete age from 0 to 60 min are approximatively 160% and 220% for the compressive strength and stiffness, respectively.

Figure 6 represents the creep strain at different early ages ($t = 0, 15, 30$ and 60 min); for each measurement, the average, the maximum and the minimum value are represented: comparing average curves it is possible to notice that the early-age creep strain decreases as the concrete hardens (maintaining the same constant load at 8 N), starting with 0.21% ($t = 0$ min) and halving in one hour.

Additionally, in Table 1, ratios between the amount of creep and the instantaneous strain are outlined; in detail, the instantaneous strain is the strain recorded until the end of the loading ramp. Such ratio grows from 5.00% at 0 min to 12.57% at 60 min. This ratio provides a dimensionless form of the early-age creep strain and it allows to evaluate the creep effect in function of the instantaneous strain.

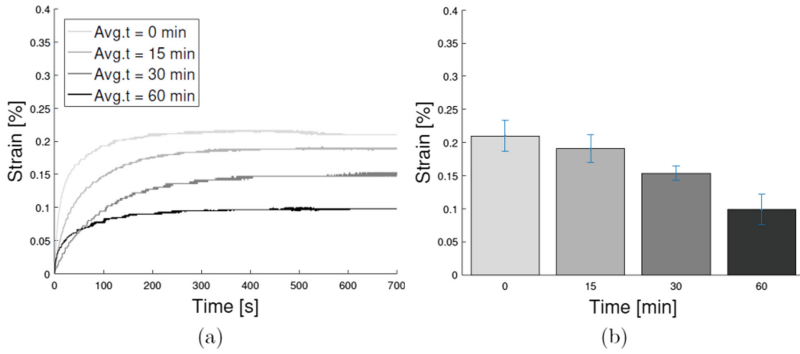


Fig. 6. Creep tests: average comparison at different time - 0 min, 15 min, 30 min, 60 min - (a) strain curves & (b) peaks with the standard deviation.

Table 1. Creep to instantaneous strain ratios in function of the curing time

Curing time t [min]	Ratio $\varepsilon_{creep}/\varepsilon_0$ [%]
0	5.00
15	8.65
30	7.81
60	12.57

4 Discussion

The outcomes of the experimental test carried out on cementitious printable mortar may be used to predict its mechanical behaviour (i.e., stress and strain state) during the printing process. Once the printing parameters are defined (Table 2) it is possible to calculate the vertical displacement related to each layer for every deposition step, supposed instantaneous.

Table 2. Printing parameters.

Layer height h_{layer} [m]	Building Rate BR [m/h]	Density [kg/m ³]
0.01	2	2411

Indeed, for the i -th stacked layer it is possible to assess the vertical stress with the following equation:

$$\sigma_i(n) = n \cdot \rho g h_{layer} \quad (1)$$

where “ n ” is the number of the filament above the i -th layer considered, “ ρ ” is the material density, “ g ” is the gravity acceleration and h_{layer} is the height of single filament. Given the curing time of the i -th layer, depending on the building rate BR:

$$t_i(n) = n \cdot h_{\text{layer}} / BR \quad (2)$$

and the vertical stress value (Eq. 1), it is possible to define the vertical strain value using the analytical surface $\sigma(t, \varepsilon)$, obtained by a cubic interpolation between the experimental stress-strain curves related to each time investigated (see Fig. 7a).

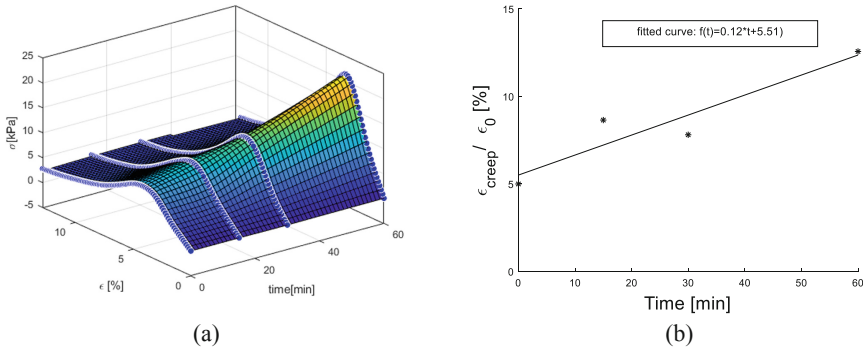


Fig. 7. (a) Cubic interpolation of the experimental stress-strain curves and (b) linear regression of the creep to instantaneous strain ratio.

The value of the vertical strain assessed is the instantaneous percentage, ε_0 , of the total strain ε_{TOT} . As shown by the experimental results, the creep strain $\varepsilon_{\text{creep}}$ grows in time under constant load; as a result, the total vertical strain of the i -th layer is given by:

$$\varepsilon_{TOT,i}(\sigma, t_0, t) = \varepsilon_{0,i}(\sigma, t_0) + \varepsilon_{\text{creep},i}(\sigma, t_0, t) \quad (3)$$

where “ σ ” refers to the stress on the i -th layer, corresponding to a load applied at age “ t_0 ”, while “ t ” denotes the time. In this study the strain assessment is based on the simplifying assumption that early-age creep is load-independent. According to Fig. 6a, a creep strain stabilisation is considered after about 700 s; as a result, the early-age creep strain is expressed exclusively as a function of the age “ t_0 ” (as in Fig. 6b). Hence, the total strain may be expressed with the following equation:

$$\varepsilon_{TOT,i}(\sigma, t_0) = \varepsilon_{0,i}(\sigma, t_0) + \varepsilon_{\text{creep},i}(t_0) = \varepsilon_{0,i}(\sigma, t_0) (1 + r(t_0)) \quad (4)$$

where “ r ” is the ratio between the creep and instantaneous strain, measured from the outcomes of the creep test (see Table 1 and Fig. 7b). Further investigations should be performed to study the early-age creep strain at different loading levels, and are ongoing by the authors.

An analytical algorithm is developed to simulate the growth of the vertical strain in each stacked layer and for each deposition step, i.e., related to the vertical stress and the evolution time. The simulation is made for a total layer's number of 49, which is the maximum number of filaments before the plastic yielding in compression (of the first layer), according to [15]. Such failure prediction, i.e., 49 layers, is based on the comparison between the vertical stress of the first layer, Eq. (1), and the compressive strength derived from the uniaxial compression test (Fig. 4). At 49 layers, the vertical displacement is equal to 8.83 mm, of which 0.64 mm are due to early-age creep effect (i.e., approximately 7% of total displacement).

5 Conclusion

The material characterisation focused on the early-age compressive response of printable mortar. In detail, the time-dependent compressive properties have been investigated (i.e. the compressive strength and the elastic modulus), including the early-age creep effect. As the resting time increased to 60 min, there was a transition from plastic to brittle behaviour, as well as an increase in strength (from 8.24 to 22.04 kPa) and stiffness (from 191.4 to 610 kPa). Concerning the creep deformation, the experimental tests have shown that the early-age creep strain decreased with the curing time, starting with 0.21% ($t = 0$ min) and halving at $t = 60$ min. Furthermore, the creep to instantaneous strain ratio is evaluated in order to have a useful tool for the vertical displacement's prediction, being a dimensionless form of the creep strain. Such ratio grows from a value of 5.00% at 0 min to 12.57% at 60 min. An analytical algorithm is developed to estimate the total vertical displacement of a printed element due to the gravity load; after 49 stacked layers, approximately 7% of total displacement is due to early-age creep strain. Such percentage may change depending on the printing parameters, on the loading level and on the specific printable mortar adopted.

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Influence of Pumping/Extrusion on the Air-Void System of 3D Printed Concrete

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Abstract. 3D printing with concrete offers many advantages over conventional construction methods and interest in this field of research has seen a rapid rise in recent years. While there have been large number of cases of successful fabrication of 3D printed structures, ensuring the long-term durability performance of the fabricated structures is equally important. Freeze-thaw damage is one such deterioration issue, especially in cold places like Switzerland. This study investigated the effect of the different processing conditions encountered in 3D printing, namely pumping, acceleration/mixing and extrusion on the air void system of a standard 3D printable mortar mix. The 3D void size distribution of the air voids obtained using a recently developed stereological model, along with the ASTM C457 results showed that pumping had the major impact on the void structure as both air content and spacing factor decreased significantly. The effect of acceleration/change in rheology and extrusion on the void structure was also prominent from the obtained results. The 3D protected paste volume (PPV) curves showed that pumping and acceleration processes could enhance the freeze-thaw performance.

Keywords: 3D printing · Freeze-thaw · Pumping · Extrusion · PPV

1 Introduction

Concrete research has been reshaped in recent years due to a host of emerging digital fabrication techniques, with 3D concrete printing/layered extrusion being the most extensively researched topic [1–3]. Compared to the conventional construction methods, this new approach offers numerous advantages in terms of cost, time, constructability and workspace safety [4]. 3D printing is a process whereby the fresh material is extruded through a mobile nozzle but, once printed, the material should support its self-weight as well as the layers placed further above. As such, an ideal printable concrete material is expected to be initially flowable between mixing and pumping (open time), next placeable with certain shape-holding ability during printing,

and then strong enough to sustain weight applied by subsequently deposited material [5]. One common way to achieve this is by the appropriate usage of chemical admixtures [6], particularly for structures with high vertical building rate. In such cases, the hydration of cement is initially retarded but then also accelerated just before the extrusion process. Such process can generically be defined as setting on demand [7].

To date, there have been a large number of successful cases of 3D fabricated structures. Engineering wise, however, the long-term durability performance of these structures deserves more attention. One pertinent issue is the freeze-thaw damage of concrete, which is especially critical in cold places like Switzerland. To cope with this problem, air-entraining admixtures have been long added into fresh concrete for enhancing the frost resistance. Experience has shown that the air content measured in the fresh state alone does not define a concrete's freeze-thaw resistance, but that this can be assessed from the spacing factor between air voids in hardened concrete [8, 9]. According to Powers, the concept of spacing factor assumes that voids are mono sized spheres which are uniformly distributed in the cement paste with a cubic lattice network [10]. For good freeze-thaw resistance, the spacing factor value should be less than 200 μm , while for high-strength concrete, it could be up to 250 μm [11, 12]. ASTM C457 describes a microscope-based method for estimating the various hardened air-void parameters [13]. However, this test is cumbersome as it involves very time-consuming repeated visual determination of the concrete material phases-aggregates, cement paste and the air voids. Another limitation of the ASTM method is that measurements are only one/two dimensional, while air void distribution is a three-dimensional concept in reality. To overcome these limitations, researchers have developed various techniques to facilitate the testing, with the flatbed scanner method being the most widely accepted [14–17].

With regard to hardened air void analysis for assessing frost resistance of concrete, the literature mentions studies about protected paste volume (PPV) [14, 18]. The PPV concept is linked to the original idea of the spacing factor and this analysis goes by the assumption that an air void has a protecting influence on cement paste (over a certain assigned range) from freeze-thaw damage. The previous practice has been to carry out this analysis on 2D polished sections of concrete and this quantifies the degree of protection by computing the fraction of paste falling into the protection range on a 2D plane [19]. However, such a 2D PPV analysis has certain limitations. The radius of an air void on an inspected surface appearing on the section tends to be smaller than the actual radius of the void, hence the protection range around an intersected air void (referred to as in-section void) would vary depending on the cut position. Also, certain sections of the inspected concrete surface may be protected by an un-intersected air void (referred to as out-section void). Thus, the 2D PPV analysis underestimates the protected range and in order to accurately estimate the degree of protection, the 3D distribution of both in and out-section voids must be determined [20]. This can be done by a stereological model recently developed by Song et al. [20]. The results obtained by this model have been found to align well with those obtained by other authors using techniques such as numerical simulation and computed tomography. Figure 1 illustrates the difference between the 2D PPV analysis and the actual protected zone [20]. In the figure, the in-section voids are shown in blue, the out-section voids in orange and the protected paste in green.

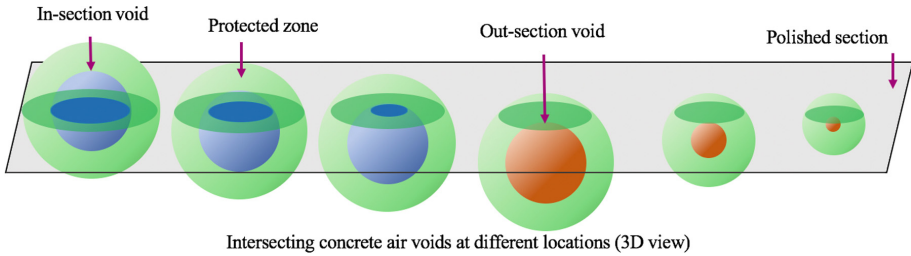


Fig. 1. Difference between 2D PPV analysis and the actual protected zone. Permission requested from [20].

Previous studies have shown that the air void system of concrete can be readily altered by the placement method during the fresh stage. This issue can be more pronounced in case of 3D printable concrete, as both pumping and extrusion can impose a greater influence than normal concrete placement methods. The potential interaction between the different chemical admixtures further complicates the situation. In this paper, the impact of the different processing conditions encountered in 3D printing, namely pumping, acceleration/mixing and extrusion on the air void system is studied. The hardened air void analysis is carried out on a standard 3D printable mortar mix after the various processing steps.

2 Materials and Methods

2.1 Material

This study was carried out based on samples cast from a single batch of mortar mix, with the different processing conditions. The batch mix consisted of crushed limestone aggregates (maximum size of 2 mm; 46% by volume), CEM I 52.5R (Holcim Normo 5R) cement, silica fume and limestone filler (8% and 15% by weight of cementitious material respectively). PCE based superplasticizer BASF MasterGlenium ACE30 (Switzerland) and 30% sucrose solution were used (1% and 0.2% by weight of cementitious material respectively). A calcium aluminate cement (CAC; Ciment Fondu, source: Kerneos) paste retarded with 0.1% sodium gluconate was used as the accelerator. The water to cement ratio for both the retarded base mortar mix and CAC paste were 0.38. After being pumped, the mortar mix was mixed with the CAC paste accelerator at the nozzle. The flow rate for the mortar mix was 1.4 L/min, while that for the accelerator mix was 54 mL/min and the residence time at the mixing chamber was 30 s. The pumping and extrusion pressures were 1.2 bar and 0.2 bar respectively. The material was collected after the different processing steps and cast into Plexiglas cylindrical molds having diameter of 9 cm and height of 12 cm, to create four different groups: Group A (Base mix retarded before pumping); Group B (Base mix retarded after pumping); Group C (Base mix extruded, but not accelerated) and Group D (Base mix accelerated and extruded). The idea behind creating these groups of mixes was to

see if the change in rheology after acceleration also has an effect on the air void system, in addition to the pumping and extrusion. One cylinder was cast (with compaction to get rid of most of the entrapped air) for each group and these were all cured in a chamber with 95% relative humidity for at least 14 days, before being worked upon.

2.2 Sample Preparation/Scanning and Image Segmentation/Processing

The cylinder samples were first saw-cut along their axis into two half cylinders which were further saw-cut into half to yield four half cylinders of 9 cm by 6 cm. These samples were then polished according to the method specified in ASTM C457 [13]. The method of sample preparation/scanning was similar to that followed by Song et al. [17].

After the polishing step, it was ensured that the surface was dried. An orange fluorescent chalk powder (Irwin Marking Chalk) was used to fill the air voids. Once all the air voids were filled, the excess powder was struck off by running a sharp razor blade over the surface at a very low angle. Care was taken not to scratch the surface during this step. All samples were then scanned with a commercial-grade flatbed scanner (CanoScan5600F) with a resolution of 4800 dpi (edge length of each pixel being 5.3 μm). In order to satisfy the minimum scanned area of 75 cm^2 , as specified in ASTM C457 [13], three samples from each group were worked upon and the size of each scan was 5 cm by 5 cm. After obtaining the scan, the next step was image segmentation. This was done using a deep learning neural network (NN) model. During the final processing, air voids smaller than 10 μm and aggregates smaller than 100 μm were removed as a noise reduction step. The pores present in the aggregates were also filled and finally, a ternary image showing the different phases was yielded. Eventually, an automated analysis was conducted to compute the various ASTM C457 parameters from the ternary images.

2.3 3D Analysis

For the computation of the various 3D parameters, a convolutional neural network (CNN) model was used. More details about the CNN model can be found in literature [21]. This model was developed based on the state-of-the-art CNN DeepLabv3 [22] and ResNet-101 [23] and has shown remarkable performance [24, 25]. PyTorch, which is an open-source machine learning library in Python was used for implementing the algorithm. The following 3D parameters were computed using the model:

- 3D void model: This shows the 3D distribution of the in and out-section voids. The out-section voids are the un-intersected voids whose protection range falls on the inspected section. These are estimated from the actual void size distribution of the in-section voids and an assumed protection range. The protection range was taken as 200 μm . The 3D protection yield (PPV map) from all voids were also obtained.
- 3D void size distribution of in-section voids: This refers to the actual void size distribution of the intersected voids. These are estimated from the 2D or apparent void size distribution of the voids on the inspected section.

- 3D paste protection: This quantifies the degree of 3D paste protected as a function of the assumed protection range. This is done based on the same principle as PPV concept.

3 Results and Discussion

A typical scan and its processed ternary image are shown in Fig. 2(a). Figure 2(b) shows the magnified versions (image section being 1.7 cm by 1.7 cm) of the top right corner of the images. This example represents the general quality of the original scans and the segmented images done by the CNN model. The processed ternary image was then used to compute the various ASTM C457 parameters and the 3D air void results.

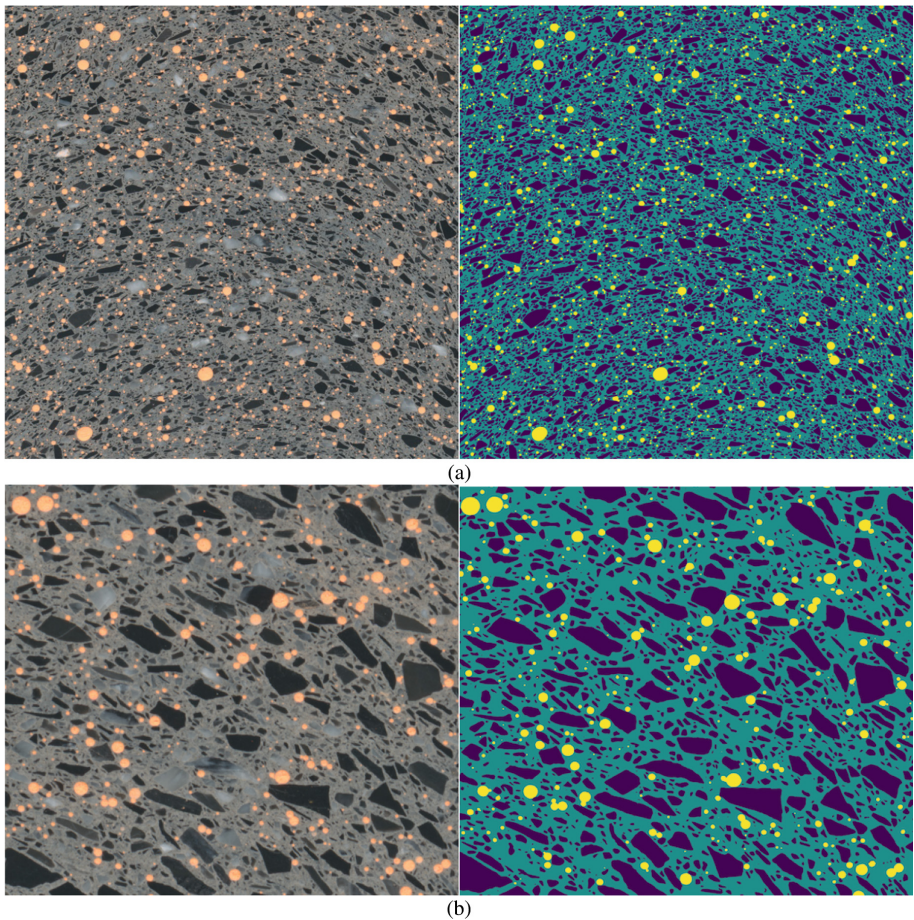


Fig. 2. (a) Original scan and its processed ternary image of sample D1 (5 cm by 5 cm); (b) magnified versions of the top right corner of the images (1.7 cm by 1.7 cm)

Based on the segmented images, the aggregate content, paste content, air content and spacing factor of the different groups of samples are shown in Table 1. The mortar mix is not freeze-thaw resistant as the spacing factor values are higher than the prescribed 200 μm [13]. The results also confirm that the pumping action does alter the void structure as both air content and spacing factor decrease. However, the difference in spacing factor values between Groups B, C and D is neglectable. The difference in air content values between them could be due to some entrapped air formed during the casting process.

Table 1. Air void parameters of the different groups of samples for three independent scanned areas of 25 cm^2 each

Group	Aggregate content [%]	Paste content [%]	Air content [%]	Spacing factor [μm]
A	38.7 ± 0.4	57.2 ± 0.9	4.2 ± 0.5	529 ± 15
B	37.7 ± 0.4	59.0 ± 0.4	3.3 ± 0.1	436 ± 1
C	38.8 ± 0.5	57.5 ± 0.4	3.8 ± 0.6	458 ± 14
D	36.1 ± 0.1	59.9 ± 0.1	4.0 ± 0.1	441 ± 20

Figure 3(a) shows the 3D void model of the top right corner of sample D1 (section size of 1.7 cm by 1.7 cm), as an example. In this figure, the blue spheres denote the in-section voids, while the out-section voids are represented by the yellow spheres. The semi-transparent shells around them indicate the assumed protection range. It is to be noted that the assumed protection range of 200 μm is an arbitrary value, which has often been taken in literature for analysis and this does not imply any real physical protection range as there is no evidence yet, to confirm this. Figure 3(b) shows the protected paste volume (PPV) map, which is available as partial size corresponding to the partial 3D model displayed in Fig. 3(a). The 3D PPV map illustrates the spatial information of the various phases. In the figure, the color annotation has been done in a way to better qualify the protection degree as function of the assumed protection range. The protected paste in the figure makes a transition from green to yellow while the red zone (for protection range above 300 μm) indicates the unprotected paste.

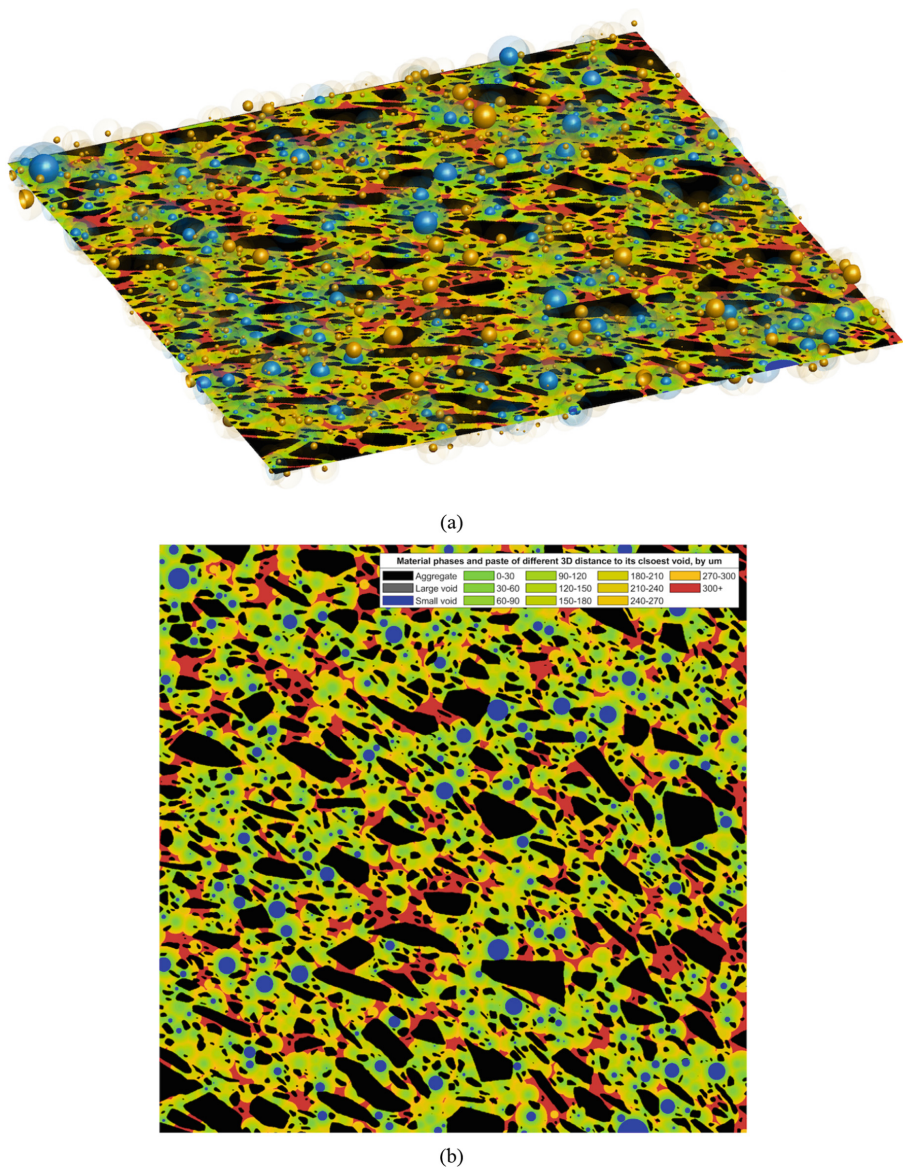


Fig. 3. (a) 3D void model of top right corner of sample D1; (b) partial PPV map of sample D1 corresponding to partial model displayed in (a)

Figure 4 shows the 3D void size distribution (VSD) of the samples from every group along with their error bars. The VSD curves show decent consistency within the same group and contrast can be seen between the different groups. Comparing Groups A and B, it is seen that the pumping breaks the ‘oversized’ air voids ($>300\text{ }\mu\text{m}$) into smaller ones such that a larger concentration of smaller voids ($<100\text{ }\mu\text{m}$) per unit

volume is seen after the pumping. This could explain the decrease in spacing factor between Groups A and B. There is also some loss of air as can be seen by the decrease in air content. The fact that pumping can alter the void structure has also been found by other researchers [26, 27]. A different observation was reported by Pleau et al. 1995 [27]. They found that pumping removes the ‘smaller’ air voids but the larger ones are little affected. However, it is important to note that their pumping pressures were much higher, of the order of 15–30 bar, in contrast to the 1.2 bar used for the current study. It is likely that in addition to the pumping pressures, the actual impact of pumping on the air void system would also depend on other factors such as mix design/rheological properties of the mix and how well air-entrained the mix is.

Although the ASTM C457 results illustrated in Table 1 show that the spacing factor did not change significantly between Groups B, C and D, a notable change is found regarding the VSD curves. In particular, the curve for Group C tends to shift rightwards. Hence, both the acceleration and extrusion (even at a pressure as low as 0.2 bar) can change the void structure. The difference in the VSD curves of Groups C and D indicates the effect of rheology on the air void system of the extruded material.

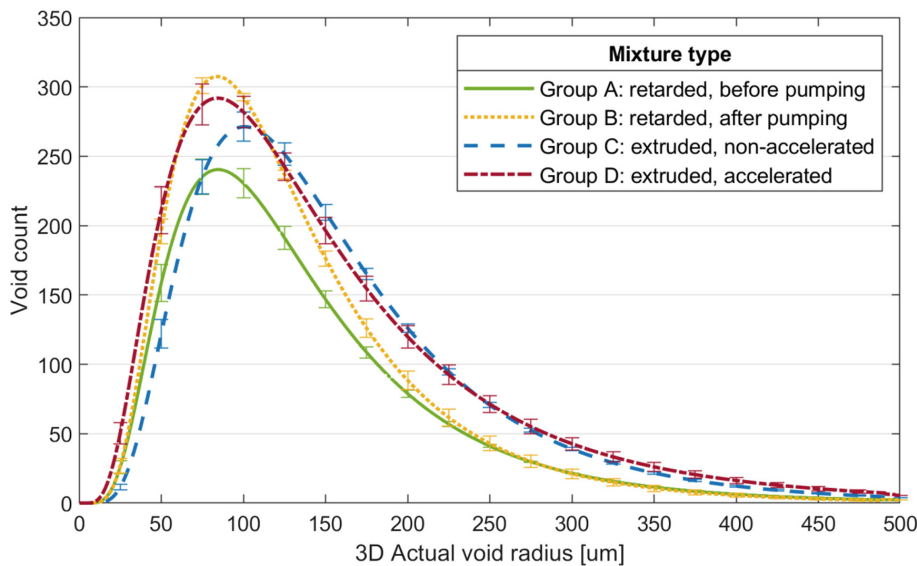


Fig. 4. Void Size Distribution (VSD) curves for different groups of samples

The degree of protection of a concrete mixture from freeze-thaw damage depends on the assumed value of protection range. Figure 5 shows the degree of 3D protection for the different groups as a function of the assumed protection range. It can be seen that the degree of protection increases non-linearly as the protection range increases. The difference in the degrees of protection between the different groups of samples can also be seen. Group C, in particular is less protected compared to the other groups. This

observation also aligns well with the 3D VSD results where it is seen that Group C has a relatively higher concentration of voids larger than 100 μm . This also supports the notion that a higher concentration of closely spaced ‘smaller’ sized air bubbles is good for freeze-thaw protection.

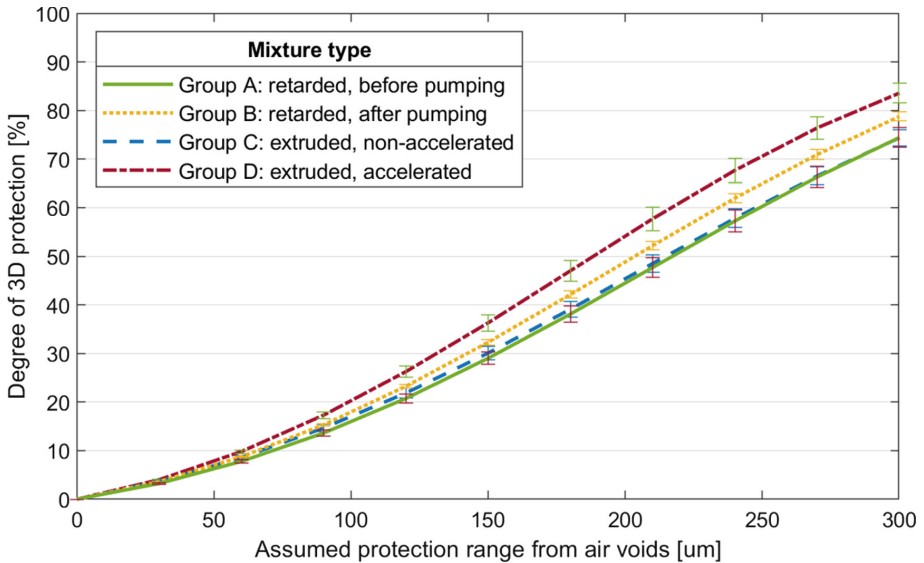


Fig. 5. Degree of 3D protection as function of assumed protection range for the different groups

Group B has a higher concentration of smaller sized air voids (<100 μm) and a smaller spacing factor compared to Group A, hence, if the mix was well air-entrained, the pumping action could possibly enhance its freeze-thaw performance. Pertaining to the requirements of 3D printing, an acceleration of cement hydration is most often necessary before the extrusion process. This also augurs well for the freeze-thaw performance as can be seen from the 3D PPV curves of Groups C and D. In short, provided the base mix is well designed in terms of freeze-thaw resistance, 3D extrusion should not compromise that property either because of processing or use of accelerators. Until such conclusions are more broadly validated, it is however recommended to test the air void spacing of 3D printed concrete that will be exposed to freeze-thaw cycles. The methods used in this paper offer a way of doing so.

As a next step in this work, the same analyses will be carried out on a 3D printable mortar mix with different levels of air-entrainment. While it is expected that air-entraining admixtures (AEAs) will lead to a more stable air-void system, it will be interesting to assess the effect of the different processing conditions on such a system. The potential interaction between the defoamers present in superplasticizers and the AEAs can possibly further affect the stability.

4 Conclusions

3D printing with concrete most often involves the following processing steps: pumping; acceleration/mixing; and extrusion. In this study, the effect of these processing conditions on the air void system of a 3D printable mortar mix was studied. The analyses was done based on the ASTM C457 results as well as 3D VSD and 3D PPV curves. It was found that pumping had the most severe impact on the air void system as both air content and spacing factor decreased significantly. The effect of acceleration/change in rheology and extrusion on the void structure was also prominent from the obtained results. In particular, Group C showed a relatively higher concentration of air voids larger than 100 μm , and it was found to be less well protected from freeze-thaw damage compared to other groups. If the mortar mix is well air-entrained, then the implications of the pumping and acceleration on the freeze-thaw performance are evident from the results.

Acknowledgements. This research was supported by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation. (NCCR Digital Fabrication, Agreement # 51NF40-141853). The authors would also like to thank Dr. Lex Reiter (PCBM group, ETH Zurich) for the useful discussions and for his support during this work and also acknowledge Heinz Richner (PCBM group, ETH Zurich) for the help in saw-cutting the hardened concrete samples.

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Fire Behavior of a Printed Sample for Building

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Abstract. Two tests have been performed at CSTB on test specimens printed in the Civil and Environmental engineering department of IMT Lille Douai. First, Compression and bending tests have been carried out at several temperatures (20 °C, 120 °C, 250 °C, 400 °C, 600 °C) on printed elements, both perpendicularly and alongside the direction of the printed layers. Temperature measurements using a thermal camera, and Digital Image Correlation analysis have been carried out.

The test results highlight that the printed material resists to an unloaded fire test without displaying any significant damage during the fire duration. The material exhibited a structural integrity as well as no leakage of the hot gas after 120 min of heating and after cooling. A comparative study of the mechanical strengths and of the thermal curvatures of the printed material according to the orientation of the layers allowed the assessment of the isotropic characteristic of the printed material and the characterization of the behavior of the joints between layers under thermal stress.

Keywords: 3D printing · Mechanical performance · Fire behavior · Cold joints

1 Introduction

The significant development of additive construction these last years in Europe has highlighted the need to facilitate its incursion within the building's technical and regulatory framework. For this purpose, the MATRICE project, carried out in 2017, defines the performance constraints required to place this kind of process on the market [1]. One of these constraints is fire safety. Indeed, under thermal stresses, the materials used to print, usually made from high performance mortar, may present the risk to peel off or to explode [4]. In the context of fire control, the evaluation of the behavior of new materials at high temperature is therefore a key subject.

2 Printing

2.1 Formulation of the Cement-Based Ink

A 3DP mortar was formulated with an Ordinary Portland Cement from Eqiom (CEM I 52.5 N), a crushed limestone sand having a particle size distribution between 0 and 2 mm from the Carrières du Boulonnais, and a superplasticizer CHRYSO Fluid Optima 100 high range water reducer (HRWR). Mixture proportions were determined at laboratory scale using a simple manual gun allowing to simulate the 3D printing of the mortar according to Khalil et al. [2]. Mix composition was determined in order to have a mortar both extrudable (able to go out of the nozzle without any blocking and filtration) and printable (possibility to superimpose about 10 mortars layers without deformation and collapse). Table 1 summarizes the composition of the formulated mortar.

Table 1. Mix composition (kg/m³).

OPC	Sand	Water (W/C = 0.31)	HRWR
905	1128	281	16.8

2.2 Printing Conditions



Fig. 1. 3 axis Cartesian printer of IMT Lille Douai (left) and printing of specimen (right).

The printing campaign was performed at IMT Lille-Douai using two 25L batches of mortar manufactured in a 80 L mixer. The mixing sequence was about 7 min for each batch. The cement was first introduced into the mixer, then water containing the superplasticizer was added and a high-speed mixing process of about 2 min was carried out. Sand was then gradually added for 1.5 min and the mixture was mixed for 4 additional minutes. During rapid mixing, the mixer was stopped and the bowl was scraped with a spatula to avoid any loss of material. After complete mixing, the mortar was poured into the pump hopper and a second batch was started 2min30 after the end of the first batch following the same sequence.

The printer was a 3 axis cartesian one (Fig. 1), whose maximal printed element dimensions were 800*800*600 mm. The printing of the two batches was successively executed.

2.3 Extraction of the Test Samples

The element printed in IMT Lille Douai was an extrusion of a rectangle. Its height was 27 cm and its thickness ranged from 50 mm at the bottom to 40 mm at the top.

Four rectangle parts were extracted from the printed element. Their dimensions were 29.0×38.0 cm, 30.0×38.5 cm, 27.0×37.5 cm, 24.5×28.5 cm.

The test program is made up of two types of experimentation:

- (a) Mechanical tests at ambient and elevated temperature: for which three of the four rectangle parts have been cut into smaller test sample (Fig. 2), reshaped in order to remove the roughness of their surface, and exposed at high temperature before testing:
- 16 specimens with the dimension of $4 \times 4 \times 8$ cm taken in the horizontal direction. They will be used for compression test and will be referred to as CI.
 - 15 specimens with the dimension of $4 \times 4 \times 8$ cm taken in the vertical direction. They will be used for compression test and will be referred to as CII.
 - 12 specimens with the dimension of $4 \times 4 \times 16$ cm taken in the horizontal direction. They will be used for three-point flexural test and will be referred to as FI.
 - 12 specimens with the dimension of $4 \times 4 \times 16$ cm taken in the vertical direction. They will be used for three-point flexural test and will be referred to as FII.

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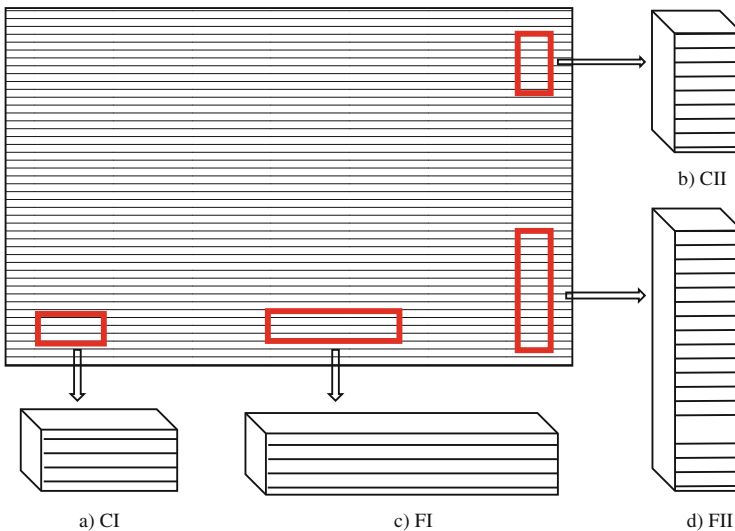


Fig. 2. The four types of sample extracted from a rectangle part before mechanical testing.

- (b) A fire resistance test, for which the remaining entire rectangle part has been dedicated (in this case, no sample has been extracted from the rectangle part: the entire rectangle part has been tested).

3 Evolution of the Isotropic Behavior of the Material with Temperature

3.1 Test Procedure

The program of the mechanical test is made up of compression tests for the CI and CII samples and also three-point bending tests for FI and FII samples (Table 2). The goal of the mechanical test is to measure how the compressive and tensile strengths would vary once the specimens were exposed to high temperature. In this study, five levels of temperature are studied:

Table 2. Testing program.

	Temperature	Number of samples				
		FI	FII	CI	CII	Total
Group0	20 °C	3	3	4	3	13
Group1	120 °C	3	3	3	3	12
Group2	250 °C	3	3	3	3	12
Group3	400 °C	3	3	3	3	12
Group4	600 °C	0	0	3	3	6

Except for group 0, the samples are heated in an electrical furnace. The heating is obtained by rising the temperature at 3 °C/min. Once the temperature in the furnace reach the required temperature, it is maintained for 1 h for samples of the group 2, 3 and 4 and for 2 h for the group 1 in order to have uniform temperature in the specimen. Afterward, the furnace is shut down and the specimens cool down naturally.

3.2 Compressive Strength

The samples have been submitted to compressive tests in the configurations displayed in (Fig. 3).

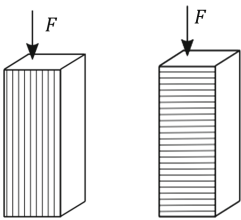


Fig. 3. Position of the specimens during the compressive test (Left CI; Right: CII)

The values of the compressive strength obtained are displayed in Fig. 4. The compressive strength has been calculated according to Eq. (1):

$$f_c = \frac{F}{A} \quad (1)$$

Where F is the maximal load and A is the section of the sample.

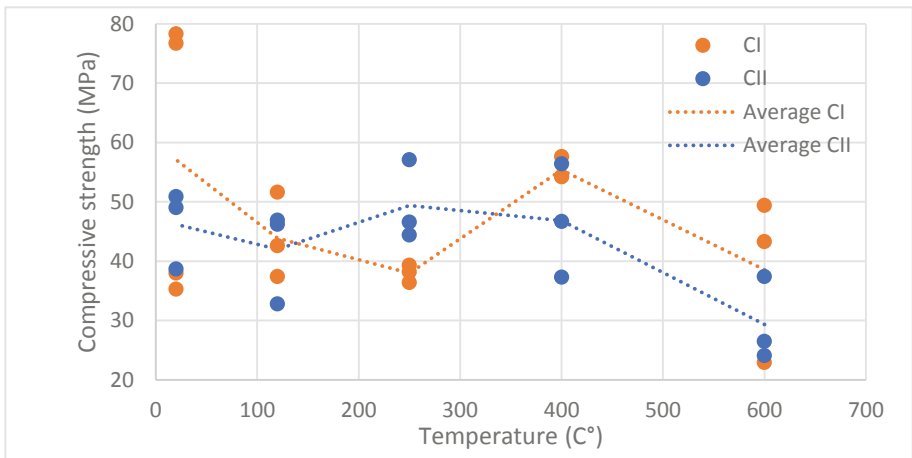


Fig. 4. Variation of the average compressive strength according to the temperature.

The compressive strength presents a slight increase between 250–400 °C and a slight decrease between 400 °C and 600 °C. These two phenomena have already been reported in researches on poured concrete [3]. The compressive strength seems to remain similar in the two directions tested at each temperature. A large dispersion of the results can be noticed for each temperature, with an average standard deviation of 9.6 MPa for the CI samples and 7.6 MPa for CII samples. A potential explanation would be that the risk of dispersion is increased for a multilayer material.

3.3 Bending Strength

The samples have been submitted to bending tests in the configurations displayed in (Fig. 5).

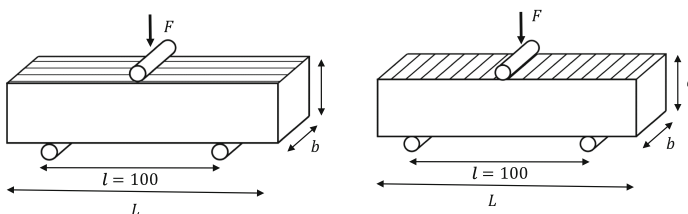


Fig. 5. Position of the specimens during the bending test (Left: FI; Right: FII)

The bending resistance can be calculated using the following equation:

$$f_f = \frac{3Fl}{2bd^2} \quad (2)$$

Where F is the maximal load, l the distance between supports, b the width, d the height.

The variation of the bending resistance with respect to the temperature is plotted in Fig. 6. The dotted curve represents the average values. It can be noted that the bending resistance of the FII samples may be more sensitive to high temperature. At 20 °C and 120 °C, the bending resistance of the FI samples and the FII samples tend to be close to each other given the dispersion, reflecting a substantially isotropic behavior. Beyond 120 °C, bending resistances of the FI samples tend to be higher than those of FII samples. This could be explained by the cold joint (bond induced by the drying between the printing of two successive layers) that may present a mechanical weakness. However, as the tested specimen is small-sized and printed all at once, the time lapse between the printing of two successive layers is limited (<30 s), and the effect induced by the cold joint should not be too pronounced.

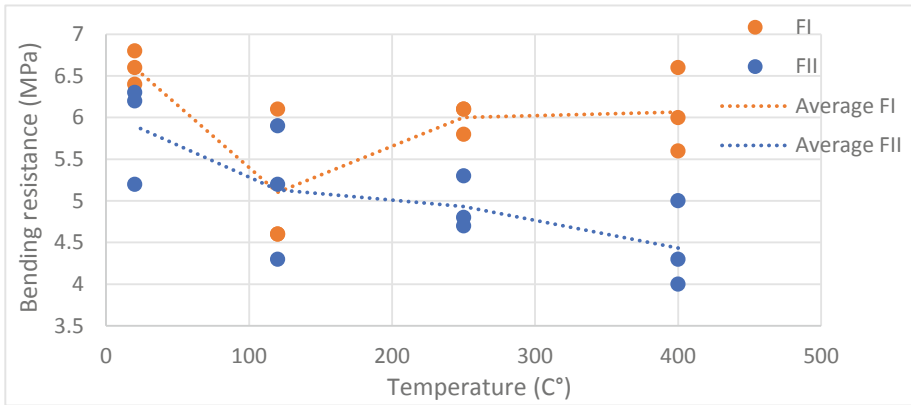


Fig. 6. Variation of the bending resistance of the samples according to the temperature.

4 Fire Resistance

4.1 Test Procedure

One side of the specimen was exposed to the fire in the furnace for two hours before it cool down naturally. The fire curve follows the ISO 834 standard:

$$T = 345 \times \text{Log}(8t + 1) + 20 \quad (3)$$

Where T is the temperature (in °C) and t is the time (in min)

During the whole test process, the specimen was fixed by clamping the lateral borders. The remaining parts of the boundary were left unrestrained, as shown on Fig. 7.

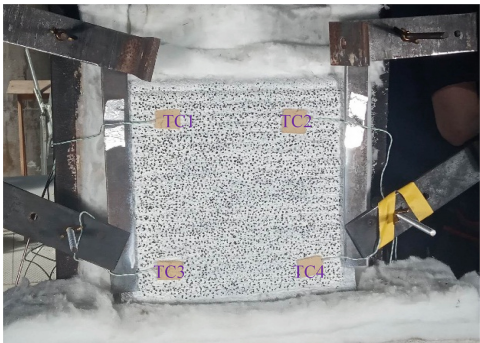


Fig. 7. Position of the four thermocouples that measure the temperature

4.2 Thermal Measures

In order to evaluate the exposition to the fire, four thermocouples have been fixed at each corner of the non-exposed side of the test body. The temperatures recorded by these thermocouples are presented on Fig. 8. Moreover, a thermal camera FLIR SC700 has been used in order to measure the distribution of the temperature (Fig. 9).

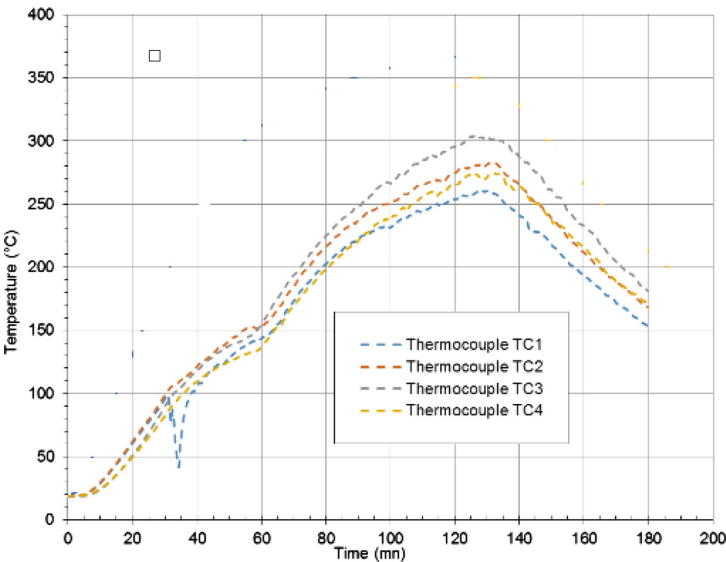


Fig. 8. Temperature recorded by the four thermocouples according to time

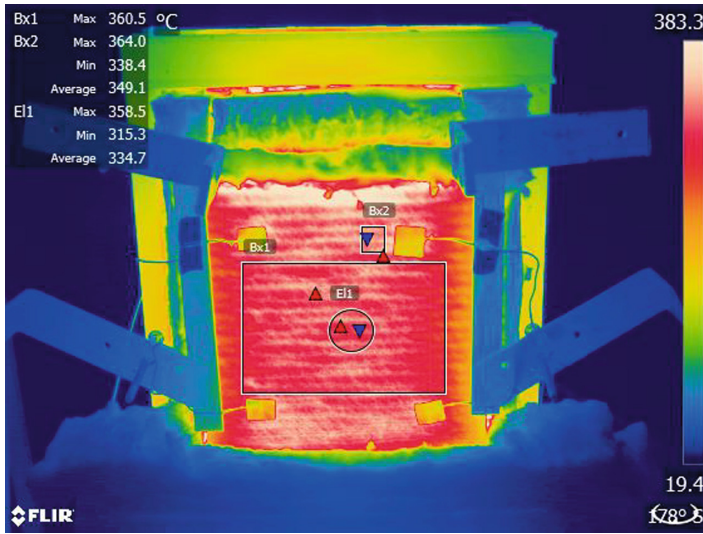


Fig. 9. Distribution of the temperature at $t = 125$ mn according to the thermal camera on the non-exposed surface.

During the heating, the thermocouples reveal a maximal difference of $40\text{ }^{\circ}\text{C}$ on the none-exposed surface (this difference is reached after 130 min of heating corresponding to a mean temperature of about $230\text{ }^{\circ}\text{C}$ for the non-exposed surface). Since the temperature on the exposed surface is close to $1000\text{ }^{\circ}\text{C}$ (generated by the ISO834-1 curve after 120 min), the material presents a thermal gradient around $700\text{ }^{\circ}\text{C}$ on 50 mm of thickness.

Regarding the homogeneity of the results given by both the thermal camera and the thermocouples, it can be supposed that the thermal solicitation of the specimen is uniform on its whole surface.

4.3 Digital Image Correlation Measures

A digital image correlation has been performed in order to measure the distribution of the out-of-plan displacement at different moments as shown in Fig. 10. The thermal gradient induced by the test leads to a thermal bending of the printed panel similar

vertically and horizontally, with a maximal deflection approaching 1.5 mm (towards the oven) at $t = 120$ mn.

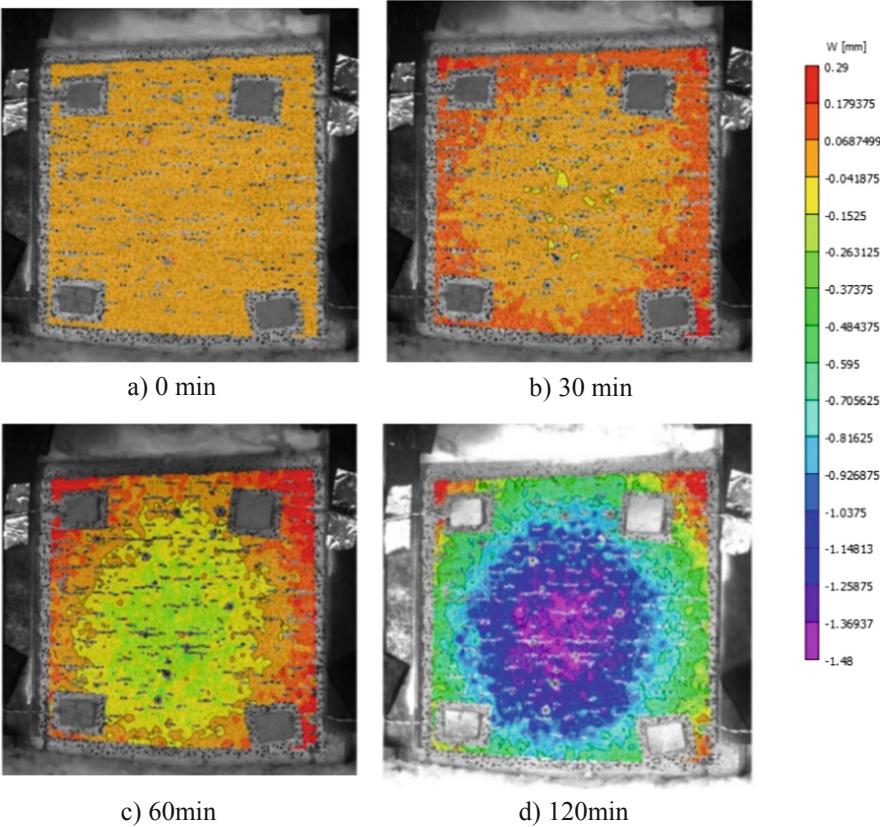


Fig. 10. Deflection measured by the digital image correlation.

The evolution on the profile of the test body during the test in the two directions has been plotted on Figs. 11 and 12.

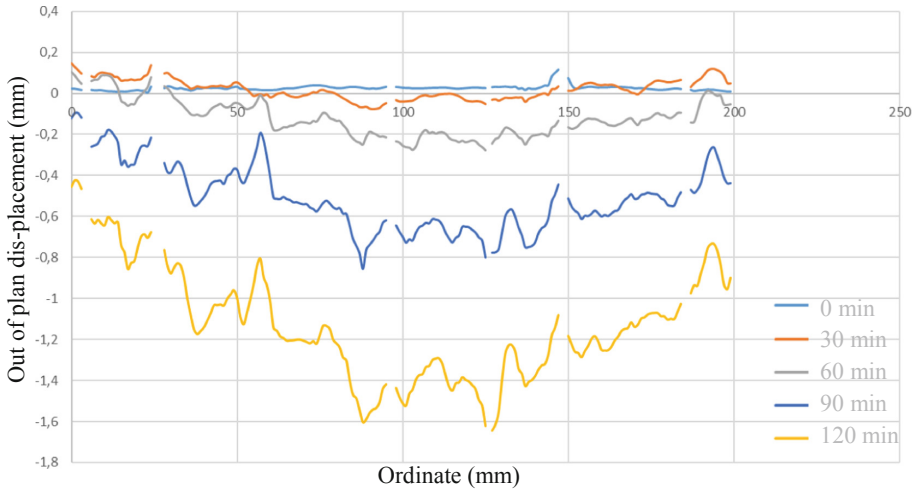


Fig. 11. Deflection profiles along a vertical line at different times

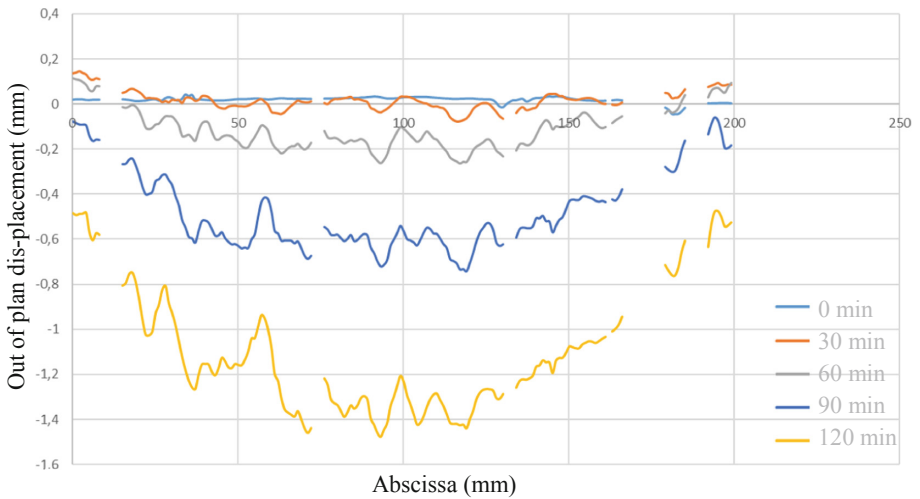


Fig. 12. Deflection profiles along a horizontal line at different times

5 Conclusion

The test results highlight that the printed material resists to an unloaded fire test without displaying any significant damage during the fire. The material exhibited a structural integrity as well as no leakage of the hot gas after 120 min of heating and after cooling. The post-cooling observations revealed the presence of non-crossing cracks in the vicinity of the horizontal interfaces between the layers on the height of the panel.

The mechanical tests tend to display a conservation of the isotropy and the stiffness of the material for the two orientations of the layers, under thermal stress. This is in accordance with the thermal curvature of the specimen which seems to be similar horizontally and vertically.

Acknowledgments. The authors wish to express much gratitude towards Pierre Pimienta and Etienne Bruchet from CSTB who helped to the design of the tests, to the technical team (Léo Gontier, Jean-François Moller, Stéphane Charuel, Olivier Jousse, François Boutin, Elliott Bombardier, Philippe Girault) from the fire resistance and mechanical testing laboratories of the CSTB for the realization of the tests and towards Guillaume Potier from IMT Lille Douai for the manufacture of printed specimens.

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Effect of Metallic Fibers on the Print Quality and Strength of 3D Printed Concrete

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Abstract. 3D concrete printing is a promising technology in the construction field. Un-availability of standards/specifications related to certification of 3D printed structures and lack of reinforcement in printed concrete are the major factors behind the under-utilization of such innovative technology. Addition of fibers as reinforcement in the printable mix could be considered as viable solution to improve mechanical properties of printable mix particularly tensile strength. In this regard, recently carried out studies have used mostly non-metallic fibers with low modulus of elasticity and tensile strength. In this study, effect of adding flexible amorphous metallic fibers on the print quality and mechanical properties (flexural and direct tensile strengths) of resulting mixes has been investigated. Fibrous and non-fibrous mixes were designed. To prepare fibrous mixes, metallic fibers were used at dosage of 20 kg/m³, 30 kg/m³ and 40 kg/m³. Further, to study the influence of fiber length on the print quality and strength, fibers of length 5 mm, 10 mm and 15 mm were used. Reference specimens for tensile and flexural strength tests were also cast in molds using all mixes used for printing. Results showed that addition of metallic fibers of length 10 mm and 15 mm exhibited detrimental effects on the print quality, however, strength values, particularly tensile strength of printed concrete were observed to be enhanced by the addition of these fibers. Although print quality of mix containing fibers of 5 mm length was least affected, no positive impact of these fibers on the mechanical strength of printed concrete was noticed.

Keywords: 3D printed concrete · Metallic fibers · Print quality · Mechanical strength · Cast-in-mold concrete

1 Introduction

3D printing of concrete is an emerging technique of construction which has attracted the attention of researchers in many countries on the globe. Unlike conventional construction technique, in 3D concrete printing, cement based material is extruded by a nozzle and deposited in layers without the use of any formwork to print structures.

Comparing to in-situ and pre-cast construction techniques, architectural freedom, cost reduction through saving in material and labor, fast production and improved efficiency and safety are the main advantages of 3D concrete printing. However, lack of conventional reinforcement and certified standards has limited the benefits that this constructing technique could have been able to offer to modern construction industry [1]. In this regard, addition of fibers as reinforcement in the printable mix could be considered as viable solution to improve mechanical properties of printable mix particularly tensile strength. Recently, few researchers have attempted to add micro fibers in the mix before extrusion as well as adding steel reinforcement during the extrusion to improve the structural performance of printed elements [1–5]. In most of the recently carried out research studies, mainly non-metallic fibers with low modulus of elasticity and tensile strength were used. In this present study, effect of adding flexible metallic fibers on the print quality and mechanical properties (flexural and direct tensile strengths) of the mix has been investigated.

2 Materials and Methods

2.1 Materials

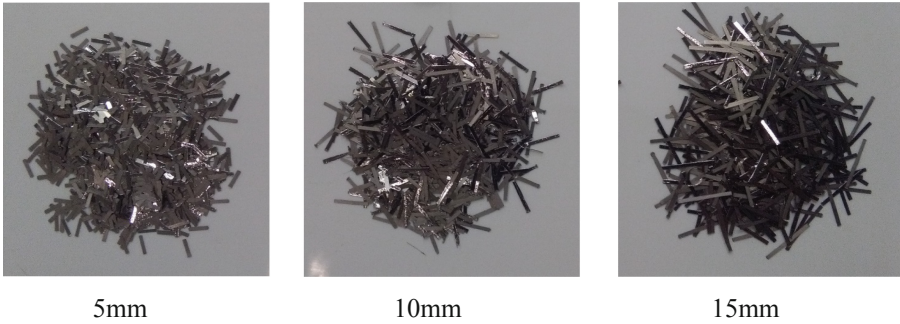
For this study, printable mortar mix was designed using CEM I 52.5 N cement (30% by weight of dry mix), limestone filler (10%), kaolin (10%), natural siliceous sand (50%), high rate water reducing (HRWR) admixture (0.4% by weight of cement) and flexible metallic fibers of three different lengths (5 mm, 10 mm and 15 mm). The water to fines (cement + limestone filler + kaolin) ratio was kept as 0.31.

2.2 Printable Concrete Mixes

In total 10 concrete mixes were prepared: one control mix without fibers and remaining nine of metallic fiber-reinforced concrete. Flexible amorphous metallic fibers of 5, 10, and 15 mm length (refer to Fig. 1) were used to prepare fiber-reinforced concrete mixes. Amorphous metallic fibers are CE certified according to NF EN 14889-1 standard. For this study, three dosages of fibers; 20 kg/m³, 30 kg/m³ and 40 kg/m³ were investigated. Detail of all ten concrete mixes with respect to fiber length, dosage of fibers and mix designation is provide in Table 1, while properties of fibers are given in Table 2.

2.3 Printing Process

U-shape objects were printed using a 3 degree of freedom printer (Delta WASP 3MTIndustrial 4.0). Printing speed was 25 mm/s. For each concrete mix, one object was printed. Information related to size of U-shape objects and test specimens saw-cut from printed objects for mechanical tests is provided in Sect. 2.4. Circular nozzle of diameter 30 mm was used for printing. Due to very small settlement of material after extrusion, width of layer varied from 30 to 35 mm (see Fig. 2), thickness of layer varied between 20 and 25 mm, while width of contact surface between layers varied from 22 to 28 mm as shown in Fig. 2.

**Fig. 1.** Amorphous metallic fibers**Table 1.** Detail of concrete mixes

Sr. No.	Mix designation	Fiber length (mm)	Fiber dosage (kg/m ³)
1	CONT	–	–
2	5FF20	5	20
3	5FF30		30
4	5FF40		40
5	10FF20	10	20
6	10FF30		30
7	10FF40		40
8	15FF20	15	20
9	15FF30		30
10	15FF40		40

Table 2. Properties of fibers

Property	Value
Length, mm	5, 10, 15
Width, mm	1.0
Thickness, μm	24
Equivalent diameter, mm	0.18
Number of fibers per kg	1100000, 580000, 385000
Specific surface (m ² /kg)	10
Density	7.2
Elastic modulus, GPa	140
Tensile strength, MPa	2000

2.4 Test Methods

Direct Tensile Strength: Displacement controlled direct tension tests were performed on printed and cast-in-mold specimens at 28 days after printing and casting, respectively. Both printed and cast-in-mold specimens were cured in air for 28 days. Loading

rate was kept as 5 $\mu\text{m}/\text{min}$ for all direct tension tests. Printed test specimens of size 10 cm $\times$ 10 cm $\times$ width (cm) according to layer width as shown in Fig. 2 were saw-cut from the two sides [each of size 220 $\times$ 240 mm] of U-shaped printed objects as shown in Fig. 4. Similarly, test specimens of cast-in-mold specimens of size 10 cm $\times$ 10 cm $\times$ 3 cm were prepared as shown in Fig. 3 and it is clear in this figure that a notch was provided at the center of each specimen. For each mix, two samples were tested and average value is reported in this contribution. Direct tension test in progress is shown in Fig. 5.

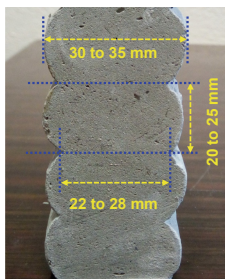


Fig. 2. Layer dimensions



Printed Concrete



Cast-in-mold Concrete

Fig. 3. Test specimens for direct tension test

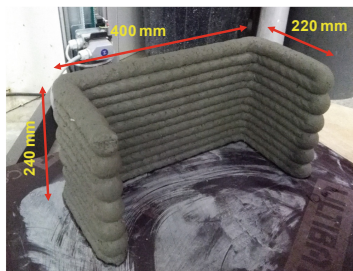
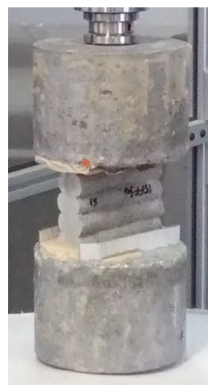


Fig. 4. U-shaped printed objects



Printed Concrete Sample



Cast-in-mold Sample

Fig. 5. Direct tension test in progress

Flexural Strength: Displacement controlled three point bending tests were performed on printed specimens with three layers and on cast-in-mold specimens using all mixes prepared for this study. Loading rate was kept as 0.02 mm/min up to 5% drop in the peak load value and then it was increased to 0.2 mm/min. The printed samples for flexural strength test were also saw-cut from the central portion of size 400 $\times$ 240 mm of U-shaped printed objects as shown in Fig. 4. For flexural testing, cast-in-mold specimens having standard size of 4 cm $\times$ 4 cm $\times$ 16 cm were also prepared and cured

in air for 28 days. The printed samples were tested for in-plane and out-of-plane bending strengths as shown in Fig. 6. For each mix, two samples were tested and average value of flexural strength is reported here.

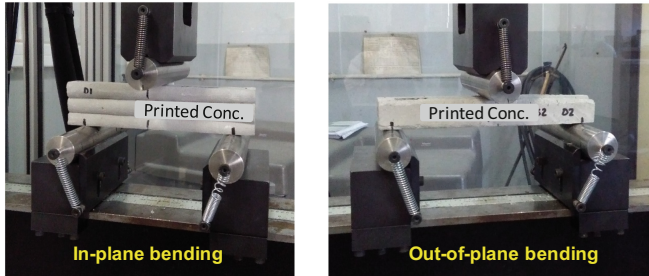


Fig. 6. Flexural tests on printed specimens

3 Results and Discussion

3.1 Print Quality

To study the effect of adding fibers of different lengths at different dosages in the mix on the print quality, printing was done using nozzle of 30 mm diameter. It was noticed that no significant change in the print quality occurred with the use of small length metallic fibers (i.e., 5 mm) even up to dosage of 40 kg/m^3 . However, print quality was affected when fibers of 10 mm and 15 mm length were added in the mix. With the increase in the contents of these fibers from 20 kg/m^3 to 40 kg/m^3 , the problem of poor print quality was observed to further aggravate. Discontinuity in the material within one layer was the major issue related to print quality. In general, no problem with respect to dimension conformity and consistency in the filaments printed using fiber reinforced concrete mixes made in this study was noticed. Layers printed with mix containing maximum dosage investigated in this study (i.e., 40 kg/m^3) of 5 mm, 10 mm and 15 mm long flexible metallic fibers are shown in Fig. 7 where it is obvious that longer fibers severely affected the print quality of layer printed with 30 mm diameter nozzle. In future, it will be interesting to study the relationship between fiber length and nozzle diameter on the print quality.

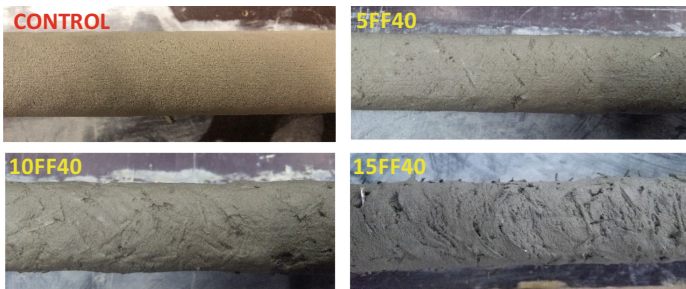


Fig. 7. Effect of fibers on print quality

3.2 Direct Tensile Strength

Tensile strength was calculated in each test using the maximum experimental force obtained divided by the average contact surface area between layers. For this purpose, after completion of each test on printed concrete, length and average width of failure surface of each specimen was measured to get the value of contact area as shown in Fig. 8, where W1, W2 and W3 are widths at different locations which were used to get average width of contact surface. In case of cast-in-mold samples, surface area after providing notch was measured and used to calculate the tensile strength.

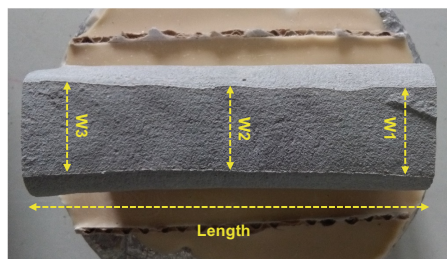


Fig. 8. Contact surface area in printed sample

Tensile strength results are presented in Fig. 9 where the tensile strength value of each mix is average of two samples tested for this purpose. The tensile strength results indicated that addition of 5 mm long fibers in concrete at dosages of 20 kg/m³, 30 kg/m³ and 40 kg/m³ resulted in decrease in average tensile strength of printed element by 3.3%, 25% and 19.7% in comparison of control mix, respectively. However, presence of 10 mm and 15 mm long fibers in the concrete resulted in enhancement of tensile strength when compared to control mix. Fibrous mixes containing 10 mm long fibers at dosages of 20 kg/m³, 30 kg/m³ and 40 kg/m³ resulted in increase in average tensile strength of printed element by 6.5%, 34% and 20% in comparison of control mix, respectively while for mixes containing 15 mm long fibers at dosages of 20 kg/m³, 30 kg/m³ and 40 kg/m³ resulted in increase in average tensile strength of printed element by 17.9%, 26% and 28.5% in comparison of control mix, respectively. Since numbers of 5 mm long fibers per kg are significantly large [refer to Table 2], presence of large numbers of fibers in horizontal direction (parallel to layer) as observed at failure surface during testing [see Fig. 12] reduced the contact area of cement matrix between two layers which resulted in less bond strength in case of mix containing fibers of 5 mm length. However, it was noticed during printing process that although print quality was adversely affected by 10 mm and 15 mm long fibers, part of few fibers coming out of the surface of already printed layer as shown in Fig. 10 acted like nails which were later on embedded into subsequent printed layer and as a result tensile strength between layers was improved which is clear from the tensile strength results obtained with mixes containing 10 mm and 15 mm long fibers. Among all fibrous mixes, as indicated above, maximum tensile strength was exhibited by fibrous mix containing 10 mm long fibers at 30 kg/m³ (10FF30) which was 34% more than that of tensile strength of control printable mix.

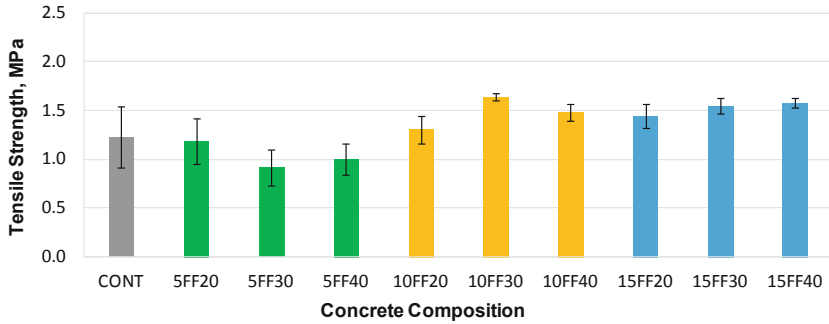


Fig. 9. Tensile Strength [printed concrete]

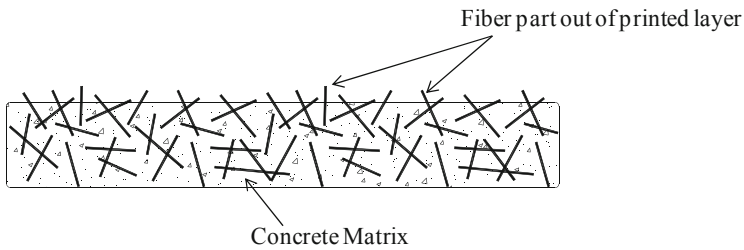


Fig. 10. Positions of fibers near surface of printed layer

Comparison of tensile strength of printed and cast-in-mold concrete samples is presented in Fig. 11 where it may be noted that results are presented for minimum (20 kg/m^3) and maximum (40 kg/m^3) dosages of fibers used in this study. Results indicated that printed concrete samples of all mixes were not able to achieve tensile strength as that of corresponding cast-in-mold concrete samples. It is pertinent to note in the results presented in Fig. 11 that as the fiber length in the fibrous mixes was increased from 5 mm to 15 mm, the difference in the tensile strength exhibited by printed concrete and cast-in-mold concrete was decreased. This observation further strengthened the idea of nailing effect with long fibers.

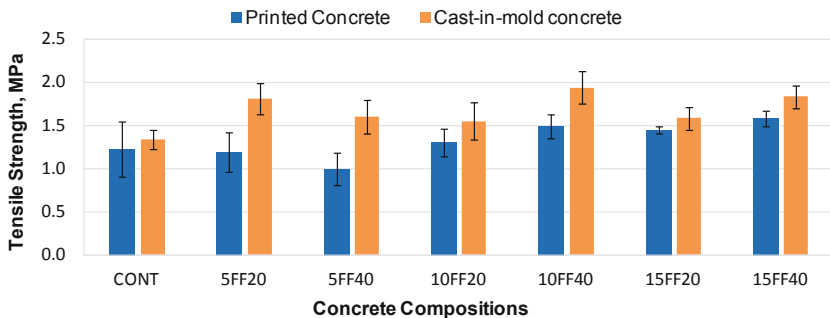


Fig. 11. Comparison of tensile strength of printed and cast-in-mold concretes

In each direct tension test on printed concrete samples, failure occurred at the interface of the layers; in no case failure occurred from within the layers. In Fig. 12, failure surfaces of printed specimens tested in direct tension are shown, where difference in the surface of mixes containing 5 mm, 10 mm and 15 mm long fibers is obvious.

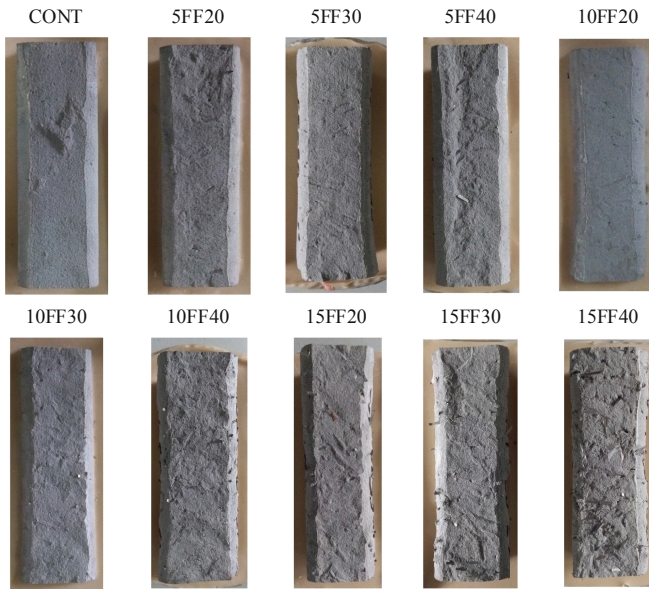


Fig. 12. Failure surfaces of printed concrete samples [direct tension tests]

3.3 Flexural Strength

In-plane and out-of-plane flexural strength values [average of two samples] of printed concrete samples and cast-in-mold concrete (named as reference) samples are presented in Fig. 13. It is obvious from these results that out-of-plane strength of each mix is greater than in-plane bending strength. The results indicated that addition of flexible metallic fibers of 5 mm length up to dosage of 40 kg/m^3 negatively affected the flexural strength of printed concrete which was found to be even lesser than that of control mix. Similarly, no effect on the flexural strength was observed with the addition of fibers of length 10 mm and 15 mm at dosage of 20 kg/m^3 and 30 kg/m^3 since flexural strength of 10FF20, 15FF20, 10FF30 and 15FF30 mixes was almost similar to that of control mix. However, mix containing these fibers at dosage of 40 kg/m^3 exhibited flexural strength value slightly greater than the control mix and among all fibrous concrete mixes, maximum in-plane and out-of-plane flexural strengths were achieved by mix containing fibers of 15 mm length at dosage of 40 kg/m^3 (15FF40) which were 9.5% and 10.3% more than the control mix, respectively. The results indicated that flexible metallic fibers of length 15 mm did not impart any distinguished positive impact on the flexural strength and addition of fibers of 5 mm in length showed detrimental effect on the flexural strength of printable concrete mixes.

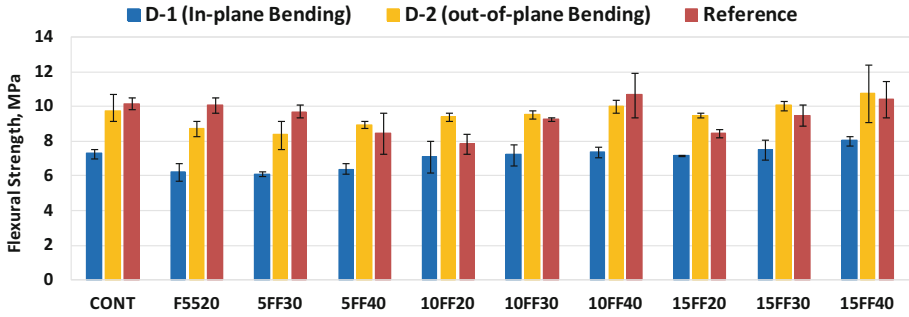


Fig. 13. Flexural strength values of printed and cast-in-mold concrete samples

Comparison of out-of-plane average flexural strength exhibited by printed concrete and reference concrete samples indicated that all fibrous printed concrete mixes exhibited flexural strength values closer to their corresponding cast-in-mold concrete mixes. Mixes containing fibers of 15 mm in length at all dosages studied here exhibited out-of-plane flexure strength values greater than attained by their corresponding reference concrete mixes. It is pertinent to mention here that similar to reference concrete mixes, all fibrous printed mixes follow almost same pattern of increase or decrease in flexural strength due to change in length and dosage of metallic fibers.

Failure pattern of printed samples of control and fibrous concrete samples tested in in-plane bending are shown in Fig. 14, where it is clear that in all cases, flexural crack travelled vertically through the layers without de-bonding of layers. In no case, crack travelled horizontally between layers. This indicates good bonding between each layer of printed elements.

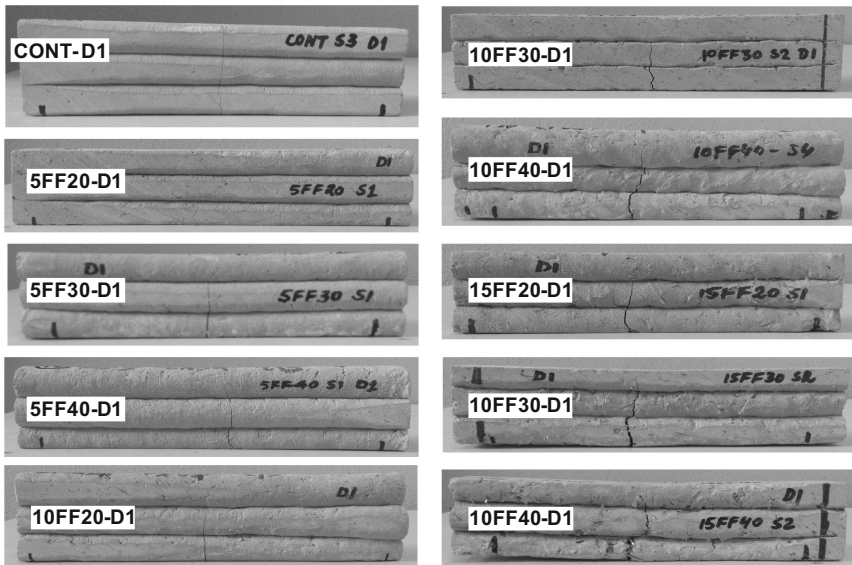


Fig. 14. Failure mode in in-plane bending of printed concrete samples

4 Conclusions

This study focused on the effect of metallic fibers on the print quality and mechanical strengths (tensile and flexure) of 3D printed concrete. Based on the findings, following conclusions are drawn:

- Use of 5 mm long fibers up to dosage of 40 kg/m^3 in concrete did not cause any notable negative effect on the print quality, however, it was significantly affected when 10 mm and 15 mm long fibers were used in concrete.
- Compared to control printed concrete, tensile strength (TS) of fibrous printed concrete was decreased due to adding 5 mm long fibers while it was increased by using 10 mm and 15 mm long fibers. In general this was true for all fiber dosages used in this study. Maximum decrease in TS of 25% was exhibited by mix containing 5 mm long fibers at 30 kg/m^3 while maximum increase in TS of 34% was exhibited by mix containing 10 mm long fibers at dosage of 30 kg/m^3 . All printed fibrous concrete mixes exhibited TS less than that of their corresponding cast-in-mold concretes. Decrease in the difference of TS between printed and cast-in-mold concretes was observed with increase in length of fibers used.
- For all fibrous printed concrete mixes, out-of-plane flexural strength (FS) was greater than in-plane FS. Compared to control printable mix, both in-plane and out-of-plane FS of fibrous printed concretes were decreased when 5 mm long fibers were added up to 40 kg/m^3 while FS values were remained same or increased for fibrous mixes containing 10 mm and 15 mm long metallic fibers. In-plane FS of all fibrous concrete mixes was lesser than FS of their corresponding cast-in-mold concrete mixes, however, no clear pattern regarding the comparison of out-of-plane FS of fibrous concrete mixes and their corresponding cast-in-mold concrete mixes was observed.

Acknowledgement. We would like to acknowledge “GA Smart Building, Toulouse-France” for providing financial support for this work and “Saint Gobain SEVA” for providing flexible amorphous metallic fibers.

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Facilitating Ductile Failure of 3D Printed Concrete Elements in Fire

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Abstract. This research investigates 3D printed concrete behaviour at elevated temperatures. Preliminary studies indicate that delamination of filament layers occurs at elevated temperatures, as opposed to thermo-hygral spalling, which typically occurs in conventionally cast high-performance concrete samples. Brittle structural failure may therefore occur during a fire scenario since little to no reinforcement is currently included in the 3DCP process. This research proposes the incorporation of steel fibres into the additive manufacturing process to facilitate ductile failure and increase interlayer mechanical properties. The fibres are vertically aligned, orthogonal to the printing plane, and strategically positioned to bridge multiple filament layers. 3D printed rectangular samples are heated via radiant gas panels and thereafter tested in four-point bending once they have cooled down to ambient temperature to determine post-fire flexural capacity and ductility properties. This study shows that steel fibre inclusion improves the structural fire performance of 3D printed elements by 33% and provides post-peak mechanical ductility to yield deflection softening. More research is required to ultimately develop a standardized economical structural fire design process for 3DCP.

Keywords: 3D concrete printing · Structural fire engineering · Steel fibre reinforcement · Experimental testing · Mechanical properties

1 Introduction

Since antiquity, structures and buildings have experienced devastating fires that resulted in the loss of life, structural damage, impaired structural integrity and negative socio-economic implications. In order to minimize the impact of such an event, structural fire engineering has developed as an immensely important discipline that quantifies the behaviour of structures subjected to high temperatures. However, an emerging technology in the construction industry, namely 3D concrete printing (3DCP) or additive concrete manufacturing, currently has negligible literature on concrete printed elements exposed to high temperatures [1].

Three primary reasons may contribute towards perturbation regarding the behaviour of concrete printed elements at elevated temperatures. Firstly, many 3D printable

cementitious materials employed by both industry and academia have high compressive strengths, which may be classified as high-performance concrete (HPC) [2]. HPC is typically more susceptible to thermo-hygral spalling compared to normal strength concrete due to the smaller free pore volume associated with higher compressive strengths [3]. Secondly, since 3DCP is an additive manufacturing technology, i.e. an object is constructed in a layer-wise manner via successive filament layer depositions, weak interlayer bonds may form (commonly referred to as lack-of-fusion) compared to the bulk material's mechanical properties [2]. Literature indicates that up to a 36% reduction in flexural strength is possible for 3D printed concrete samples due to lack-of-fusion [4]. These weak interfaces, together with typical thin-walled filament 3DCP construction, may possibly be negatively affected by self-equilibrating mechanical stresses resulting from thermal strains [5]. Thirdly, a process is yet to be developed that automatically includes steel reinforcement in the 3DCP construction process, although many attempts have been made to this end [6, 7]. Consequently, 3D printed concrete elements lack ductility and confinement and may experience brittle failure in the event of crack initiation from the effect of high temperatures.

This research presents an initial experimental investigation into the behaviour of 3D concrete printed elements at elevated temperatures. Unrestrained printed concrete samples are heated via an incident heat flux and tested in four-point bending after cooling to determine its post-fire residual flexural strength. Steel fibres are incorporated between filament layers (positioned orthogonally to the print-plane) as an attempt at providing ductility and improving the weak interlayer bonds, which together may improve the structural fire performance of 3DCP elements.

2 Experimental Setup

2.1 Materials and Sample Preparation

A total of twenty samples were prepared for testing of which (i) ten contained no fibres (NF) and (ii) ten contained steel fibres (SF). (iii) Five samples from each group were heated (NF_H and SF_H) and thereafter tested in flexure while the remaining five samples did not experience any heating (iv) before testing them in flexure (NF_A and SF_A). A 40 mm thick rectangular hollow section was 3D printed, whereafter twenty samples were saw-cut to $160 \times 40 \times 40$ mm ($L \times W \times H$) from the rectangular section and cured in a climate controlled room at 23 °C and 65% relative humidity until testing at 28 day concrete age. At 60 mm/s printing speed, a pass time of 35 s between successive layer depositions is obtained. The cementitious mixture employed for the printing has a water to cement ratio of 0.45 and a 28-day compressive strength of 70 MPa, therefore classifying it as an HPC [2]. All the constituent quantities are given in Table 1. DRAMIX 3D 65/60BG steel fibres of length 60 mm and diameter 0.9 mm were employed; however, the hooked ends were cut off to prevent disturbance of the concrete sample when inserting it, which yielded a final length of 50 mm. The fibres have a tensile yield strength of 1160 MPa and elastic modulus of 200 GPa. The steel fibres were manually inserted during the printing of the rectangular section and placed in the center of the filament, i.e. on the neutral axis when testing a sample in flexure.

A lap distance of approximately one filament layer height (15 mm) is provided to ensure that the fibres always bridge the interlayers. Each concrete sample in categories SF_H and SF_A contains one steel fibre located in the center of the 40×40 mm cross-section, which is where the tensile stress originates for 3DCP elements in fire. Note that fibres are so positioned to primarily improve ductility rather than post-crack strength and ensures consistency when placing the fibres into the concrete during printing. Figure 1 depicts the printing of the rectangular section that incorporates the fibre placement. An undulating surface finish is obtained due to over extrusion of the filament to yield a 40 mm layer width, as the nozzle is only 25 mm in diameter.

Table 1. 3DCP mix constituent quantities.

Constituent	Description	kg
Cement	PPC SureTech 52.5 N	579
Fly ash	DuraPozz Class F	165
Silica fume	SiliconSmelters MicroFume	83
Fine aggregate	Local Malmesbury (4.75 mm max. size)	1167
Water	Potable Tap Water	261
Superplasticizer	Chryso Premia 310	5.75

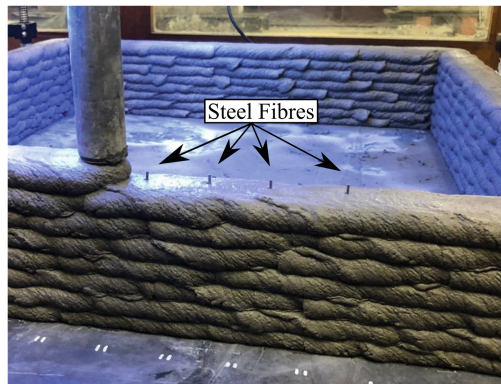


Fig. 1. 3D printing of the rectangular hollow section from which the $160 \times 40 \times 40$ mm samples were saw-cut. 50 mm long straight steel fibres were manually inserted into the concrete during printing and purposefully positioned to be in the center of the 40 mm filament width.

2.2 One-Dimensional Heat Conduction Setup

In order to best understand the complex behaviour of 3DCP at elevated temperatures, the experimental setup was simplified to represent a one-dimensional heat conduction scenario, as depicted in Figs. 2a and 2b. The samples were exposed to direct radiation of approximately $50\text{--}60 \text{ kW/m}^2$ via four gas radiant panels acting perpendicular to the front face of the samples. The samples were heated until the front and back face

reached 500 and 200 °C respectively, taken as the average of the five samples heated simultaneously. The sides of all the samples were completely covered with ceramic blanket, while the backsides were kept exposed to the environment in order to simulate one-dimensional heat transfer. The samples were not restrained against thermal expansion. A 50 mm standoff distance between the radiant panels and the samples were maintained. A heat flux gauge is fixed above the specimens in the vermiculite board to monitor heat flux exposure during testing.

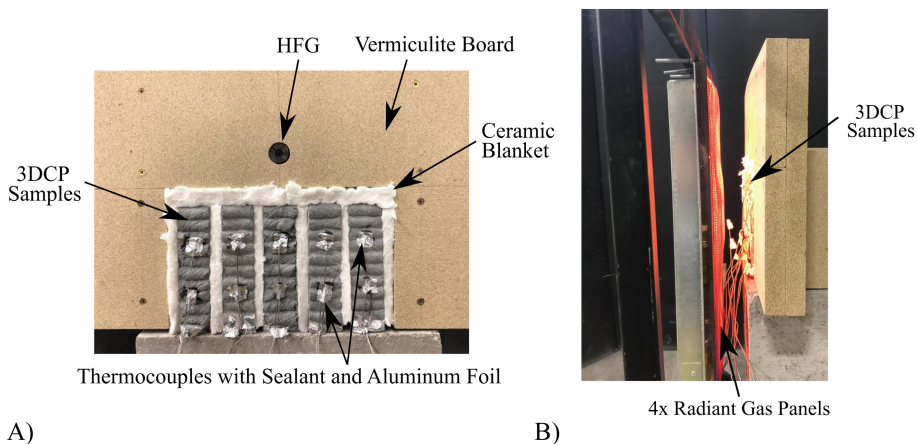


Fig. 2. Experimental test setup for thermal radiation indicating A) the front face of the five 3DCP prisms equipped with TCs and B) the radiant gas panels spaced 50 mm from the samples.

The instrumentation layout consists of 1.5 mm K-type thermocouples (TCs) employed for temperature measurement, connected to an Agilent 34980A data logger, with a 4-wire resistance temperature detector used to measure the external reference temperature. Each sample was equipped with four TCs in total, two on the front face and back face respectively. The TCs were attached to the sample surface by drilling a small hole of 1.5 mm in diameter and depth and inserting the tip of the TC into the hole. The back of the tip is then sealed-off with a small amount of fire sealant (which did not make contact with the tip) and thereafter covered with aluminum foil tape to prevent radiation from influencing TC readings. The TCs are spaced across the longitudinal direction of the prisms at third-point intervals.

2.3 Mechanical Test Setup for Four-Point Bending

The flexural strengths of the concrete prisms were determined after the samples had cooled down to ambient temperature, which was the day following heating (i.e., 29-day concrete age). Ideally, the mechanical testing of the prisms should be conducted while the prisms are at the relevant elevated temperatures for proper in-situ results; however, Stellenbosch University does not possess over the required infrastructure to perform such testing. The methodology presented in EN 196-1 [8] was adopted for the flexural

testing and executed using the Zwick Z250 material testing machine. Figure 3 depicts a schematization of a four-point bending test conducted on a 3D printed sample. The filament layers are vertically aligned in order to obtain normal stresses perpendicular to the interlayer planes induced via bending. In this manner, any cracks that may have developed during heating (whether in or in-between filament layers) may be exploited to measure the structural performance contribution of the steel fibres.

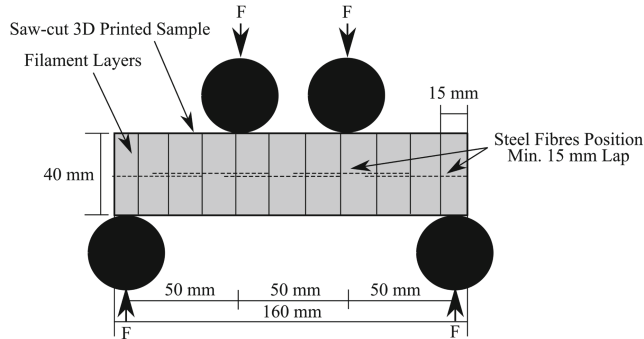


Fig. 3. Schematized four-point bending test setup of a saw-cut 3D printed concrete prism sample containing steel fibres.

3 Results and Discussions

3.1 Temperatures

The time-temperature response curves for NF_H and SF_H are depicted in Figs. 4a and 4b respectively. In both cases, the front face of the samples heated up significantly faster than the back face that reached 200 °C after approximately 40 min. Explosive thermo-hygral spalling did not occur in any sample. No major inconsistency in the rate of heating is observed between the NF_H and SF_H samples. However, technical difficulties were experienced with the gas burners during testing, where one of the four would frequently shut down for roughly 20 s at a time due to unknown reasons, as is evident in Figs. 4a and 4b. Although a decrease in front-face temperatures is consequently obtained, it is believed that the overall influence on the test procedure is trivial. A constant increase in back-face temperature is experienced even when only three of the four burners were operational. This behaviour is also likely to occur for the internal bulk concrete over the sample width, with the exception of the front face that is sensitive towards a change in heat flux. An interesting observation to take note of is the ongoing increase in back-face temperature experienced for approximately 10 min after the burners have been shut off. It is deduced that additional weakening of the concrete microstructure may occur after a fire has been extinguished. Due to safety reasons, it could not be visually determined if any cracking occurred during heating or cooling. The cross-sectional temperature across the width of the filament samples was approximated using Wickström's method [3] and is also depicted in Figs. 4a and b.

An approximately linear decrease in temperature is obtained as a function of depth measuring from the front-face, for up to about 75% of the total filament width, whereafter the temperature plateaus. It can now be determined that the average concrete temperature at the position of the steel fibre in samples SF_H reached approximately 250 °C after 40 min.

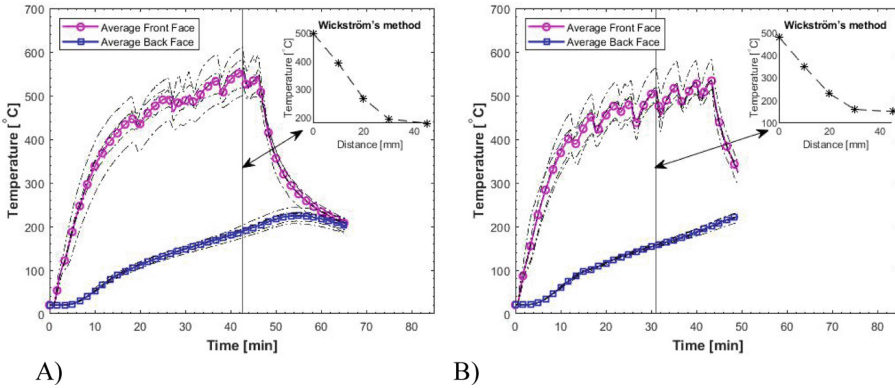


Fig. 4. Front and back face temperatures of the 3DCP samples A) without steel fibre addition (NF_H) and B) with steel fibre addition (SF_H), as well as the approximate cross-sectional temperature distribution over the width of the filament layers.

3.2 Mechanical Properties

No Fibre Inclusion (NF_A & NF_H). The unheated (NF_A) samples performed considerably better in four-point bending than the samples that were heated by the gas panels and tested after cooling down (NF_H), as depicted in Fig. 5. The average flexural breaking stress of the NF_A samples is 2.99 MPa compared to 0.81 MPa for NF_H. Therefore, as in agreement with literature and various concrete design norms, heating of concrete reduces its strength considerably. In this research, a 73% reduction in flexural strength is observed for 3DCP prisms after being exposed to elevated temperatures. Every failure during testing occurred precisely on an interlayer, i.e. the contact surface between two filament layers, which is attributed to the lack-of-fusion. One specimen from the NF_H group delaminated via manual handling after testing and could not be tested in bending. The variability in flexural strength of the NF_H samples is considerably higher than that of the NF_A samples, 50.5% compared to 9.65%. These results all indicate that 3DCP elements would not perform well in a fire situation as they either i) delaminate due to manual handling (low force or own weight) just after or during heating or ii) retain insignificant flexural or interlayer bond strength (27%) after heating and cooling for structural load bearing applications (Tables 2 and 3).

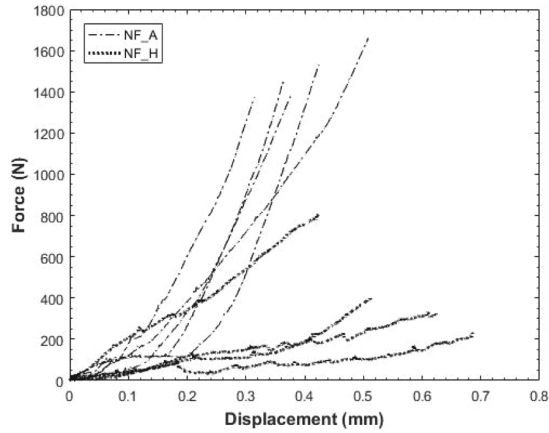


Fig. 5. Force-displacement diagram indicating both NF_A and NF_H samples' response in four-point bending, where the force on the y-axis equals 2F in Fig. 3.

Table 2. Four-point bending test results for 3D concrete printed prisms without steel fibre inclusion (NF_A & NF_H).

Sample type	Sample number	Breaking force (N)	Flexural stress (MPa)	Average flexural stress (MPa)	CoV (%)
NF_A	1	1458	2.75	2.99	9.7
	2	1380	2.61		
	3	1373	3.17		
	4	1661	3.13		
	5	1531	3.27		
NF_H	1	369	0.7	0.81	50.5
	2	Delaminated after heating			
	3	234	0.42		
	4	402	0.74		
	5	805	1.39		

Single Steel Fibre Inclusion (SF_A & SF_H). The SF_A samples performed as expected in four-point bending. A 9% increase in average maximum flexural strength is observed compared to that of NF_A (3.27 vs 2.99 MPa), however, the variability of SF_A is 7% higher than that of NF_A. Therefore, it is deduced that steel fibre addition has a negligible influence on the maximum ambient flexural strength, as confirmed with a one-way ANOVA test ($F(1, 7) = 1$, $p = .35$). No delamination was reported for the SF_H samples during or after heating, compared to the one sample from the NF_H group. Steel fibre addition may therefore possibly prevent complete delamination of 3D printed filament layers during or immediately after heating in the event of a fire, hence improving structural fire performance and/or compartmentation.

A 69% reduction in maximum flexural strength is obtained for SF samples that have been exposed to elevated temperatures (SF_H), compared to the 73% reduction obtained for NF samples after heating (NF_H). This mere 4% difference is insignificant to deduce any significant conclusions. However, when considering that the SF_H samples' flexural capacity is 33% greater than that of the NF_H samples (1.08 vs 0.81 MPa), together with an 8% decrease in the variability of results, it seems that steel fibre addition may potentially be beneficial for post-fire mechanical performance of 3DCP elements. A one-way ANOVA test proves otherwise ($F(1, 7) = 0.82$, $p = .39$), but more samples are required to reach a confident conclusion due to the high CoVs. A more favorable result may have been obtained if fibres were placed further away from the neutral axis, i.e. in the tension zone. Nevertheless, the average post-peak flexural capacity of the SF_H samples is 2.8 times greater than that of the SF_A samples (0.45 vs 0.16 MPa). The reason therefore remains unknown and requires complementary research.

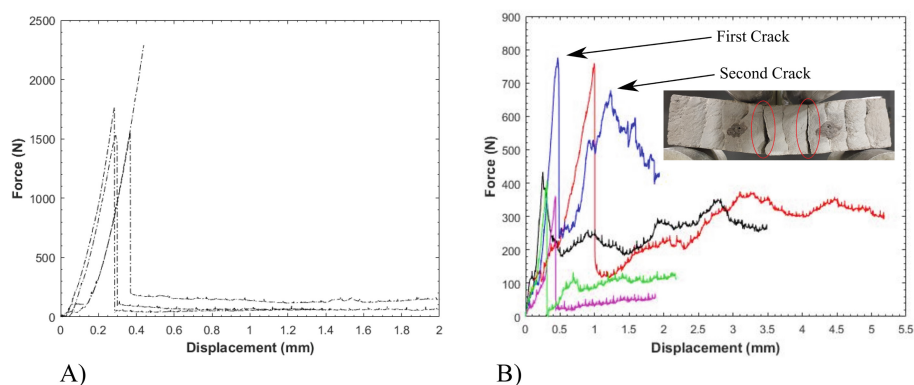


Fig. 6. Force-displacement diagrams indicating A) SF_A samples' response in four-point bending and B) SF_H samples' response in four-point bending, where the force on the y-axis equals 2F in Fig. 3.

Deflection softening behaviour is observed in the SF_H samples (see Fig. 6b) and may therefore yield ductile failure in 3DCP elements in fire, compared to the brittle failure observed in the unreinforced NF_H 3DCP prisms. Multiple cracks were observed in some of the SF_H samples during flexure testing. Although the post-peak flexural capacity is relatively insignificant, it can be improved by i) using more or larger steel fibres for reinforcement and ii) positioning the fibres further away from the section's centroid axis (i.e. closer to the filament layer's lateral edges), which may in turn possibly yield deflection hardening. These results indicate that orthogonal steel fibre addition has the potential to improve structural fire performance of 3DCP elements both during and post fire by facilitating ductile failure (Table 3).

Table 3. Four-point bending test results for 3D concrete printed prisms with steel fibre inclusion (SF_A & SF_H).

Sample type	Sample number	Breaking force (N)	Maximum flexural stress (MPa)	Average flexural stress (MPa)	CoV (%)
SF_A	1	2289	4.06	3.27	16.6
	2	1565	3.04		
	3	Technical error occurred			
	4	1529	3.11		
	5	1766	2.85		
SF_H	1	759	1.62	1.08	42.6
	2	433	0.82		
	3	361	0.67		
	4	776	1.54		
	5	407	0.75		
Average post-peak flexural capacity of SF_A samples (MPa):					0.16
Average post-peak flexural capacity of SF_H samples (MPa):					0.45

4 Conclusions

This research investigated the structural fire performance of 3DCP elements at elevated temperatures. Prism samples with (SF) and without orthogonally placed steel fibres (NF) were heated (SF_H & NF_H) and after cooling down to ambient temperature mechanically tested in four-point bending. The following main conclusions are drawn from this research:

- 3DCP samples delaminate between filament layers under self-weight possibly during or after being exposed to high temperatures (NF_H). This may result in brittle failure since no steel reinforcement is present in typical 3DCP elements.
- Orthogonal steel fibre addition between filament layers improves the structural fire performance of 3DCP elements by providing post-peak flexural capacity and thereby inducing deflection softening to facilitate ductile failure (SF_H). Enhanced post-peak flexural capacity can be obtained by positioning the fibres further away from the centroid.
- Multiple cracks form in bending testing of the samples including steel fibres (Fig. 6b). This may compromise structural integrity and result in durability issues; however, the safety of 3DCP elements is improved compared to unreinforced elements.
- 3DCP elements typically consist of multiple sections, and the increased ductility highlighted in this work will allow for greater load redistribution at high temperature, thereby reducing the chance of failure.

Based on the above, active and/or passive fire protection measures are currently recommended for 3DCP elements/buildings that may be exposed to fire. Ultimately,

this study aims to shed light on the structural fire performance of 3DCP elements to thereby motivate for more detailed research to be conducted. A standardized economical fire design is envisaged to accompany the constructability design process for 3DCP [9].

Acknowledgements. The authors acknowledge the financial support received from the Department of Trade and Industry of South Africa under THRIP Research Grant TP14062772324 as well as the Lloyd's Register Foundation under the "Fire Engineering Education for Africa" grant.

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High-Performance Light-Weight Concrete for 3D Printing

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Abstract. The aim of this experimental study is to develop high strength, lightweight concrete mixture suitable for 3D printing in construction. This work investigates the effect of replacing normal aggregate either partially or totally with expanded perlite aggregate. This material allows for better thermal insulation properties, thus decreasing the energy usage within the life cycle of the concrete structure. Expanded perlite aggregate was used in concrete by 20 vol.-%, 40 vol.%, 60 vol.%, 80 vol.-% and 100 vol.-% in replacement of the natural aggregate. Material characterization tests of compressive strength, flexural strength, and thermal conductivity were carried out for six concrete mixtures. The proposed concrete mixture, which has 100% of expanded perlite aggregate achieved reduction percentage of thermal conductivity around 62% (0.69 W/mK) relative to normal weight concrete the mixture has a compressive strength of 42 MPa at 28 days. This mixture is appealing for 3D printing in 3D concrete printing as it reduces the environmental impact of the built environment by improving the thermal insulation and decreasing the energy consumption during building operation phase.

Keywords: High-strength concrete · Additive manufacturing · 3D concrete printing · Light-weight concrete · Expanded perlite · Thermal insulation · Microstructure analyses

1 Introduction

Over the years, climate change and increase in the release of greenhouse gases including carbon dioxide has been of major concern. Energy production is the main source of greenhouse gases and the main cause of climate change issues. More so, it is important to note that approximately one-third of energy consumption is expended by the building sector and is expected to reach 42% by 2030 [1–3]. Specifically, the

operation phase of buildings accounts for 73% of the energy consumption of which about 60% is used for heating, ventilating and air conditioning [4, 5].

Consequently, in order to reduce the adverse effect on the environment by the construction industry, it has become important that materials used are good thermal insulators which greatly improves the energy efficiency of buildings i.e. buildings with good thermal insulation properties greatly reduces the energy consumption being used in heating/cooling of buildings. Typically, thermal insulation of buildings is achieved by incorporating insulation materials within the building walls and increasing the thickness of building envelopes. This however increases wall thickness, which is not desirable due to space restrictions, costs, transport volumes, architectural restrictions, etc. Therefore, researchers have focused on exploring methods to enhance the thermal insulation of concrete material [6–8]. Thermal conductivity, which is the ability of a material to transmit heat, is the property of main concern when evaluating thermal properties of concrete. Concrete made with commonly used aggregates has a thermal conductivity of 1.7 to 2.5 W/mK which is fairly large, thus exhibiting poor insulation properties [9, 10]. The thermal property of concrete is directly connected to its components (aggregate type, aggregate proportion, moisture content, air voids and any additional cementitious material). Thus there has been many research to investigate various aggregate types, proportions and their relationships with thermal properties of concrete [11] leading to the growing popularity of perlite.

Expanded Perlite (EP) is formed by heating perlite from 760 °C to 1,100 °C as perlite is a hollow and porous siliceous volcanic glass whose volume rapidly expands to 20 times of its original volume when heated [12] thus making it a lightweight material and as air has a very low thermal conductivity compared to water, EP exhibits excellent thermal insulating properties [13–15]. The effects of EP on the mechanical and thermal properties of lightweight concrete was tested in [16]. It was shown that thermal conductivity decreased as the weight per unit of the concrete decreased (i.e. as a higher volumetric amount of aggregate is replaced with EP) but the compressive strength reduced greatly. Decreased thermal conductivity properties and a slightly reduced mechanical strength of self-compacted concrete was recorded when 10 vol.-% of the fine aggregate was replaced with perlite [17].

Similar studies [18–21], experimented with replacing varying proportions of normal aggregate with EP to achieve a reduced thermal conductivity. The result of the experiment showed good and desirable thermal conductivity and thermal properties, but the reduced strength of these mixtures rendered them unfit for use for structural purposes. A major problem of adjusted concrete mixtures having low strength has been faced by lot of researchers in the feat of developing a light weight and a thermal insulating concrete and this make them unfit for certain types of applications.

This paper presents an experimental evaluation of the influences of EP on thermal properties and mechanical properties of high-performance concrete, a study that is driven by the desire to develop a lightweight concrete that retains its mechanical strength and still has reduced thermal conductivity beneficial for insulating purpose and at the same time suitable for 3D concrete printing.

2 Experimental Procedure

2.1 Material and Mix Design

For the experiment in this work, ordinary Portland cement, micro silica, fly ash, river sand with a maximum particle size of 2 mm, EP with a max particle size of 4 mm, and polypropylene microfibers with a length/diameter ratio of 12/0.18 mm were employed. The polypropylene microfibers were used to reduce shrinkage and deformation in the plastic state. Polycarboxylic Ether superplasticizer, provided by BASF, was used to maintain concrete workability with a low water/cement ratio (W/C). Alkali-free accelerator was used only in the printing process to control the setting and hardening times.

The grading of the sand, cement, fly-ash, and micro-silica was measured using the Beckman Coulter LS 13 320 machine. However, because of the large size of the EP aggregate (>2 mm), sieves analysis was implemented as per the ASTM D546-10 standard.

Figure 1 illustrates the grading curves of all materials used in this work as a function of the sieves size.

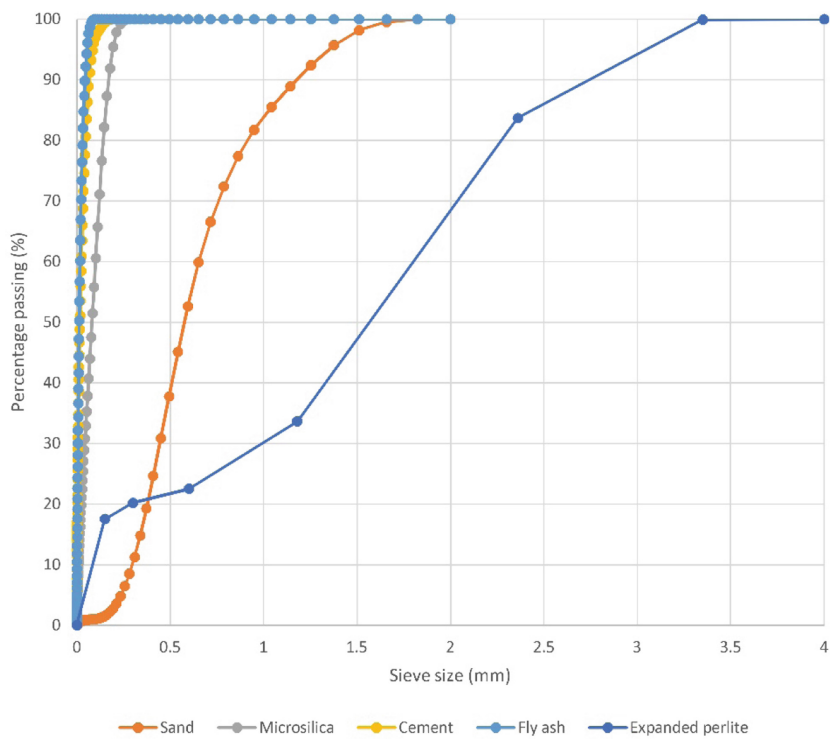


Fig. 1. Particles size distribution of the raw materials

2.2 Material Preparation

To evaluate the result when EP aggregate replaces a normal aggregate, six different mixtures of concrete was prepared having the same W/C ratio of 0.28. The replacement was done in increments of 0, 20, 40, 60, 80, and 100% of the volume of the sand while keeping the cementitious binder (70 wt.-%, 20 wt.-%, and 10 wt.-%, of Ordinary Portland Cement (OPC), fly ash and densified micro-silica) the same for all the six mixtures.

The manufacturer's recommended dosages of superplasticizer (i.e. 1 wt.-%, of cementitious material) and microfiber (i.e. 1.2 kg/m³) were used. In Table 1 is the lists of materials used in the six mixtures with their various ratio of mixture.

Table 1. Mix proportions of the six mixtures.

Concrete codes	NC	EPC20	EPC40	EPC60	EPC80	EPC100
EP ratio	0 vol.-%	20 vol.-%	40 vol.-%	60 vol.-%	80 vol.-%	100 vol.-%
Sand (kg/m ³)	1241	992.8	744.6	496.4	248.2	0
EP (kg/m ³)	0	12.77	25.55	38.32	51.09	63.86
Cement (kg/m ³)	579	579	579	579	579	579
Fly ash (kg/m ³)	165	165	165	165	165	165
Micro silica (kg/m ³)	83	83	83	83	83	83
Water (kg/m ³)	232	232	232	232	232	232
Micro fibre (kg/m ³)	1.2	1.2	1.2	1.2	1.2	1.2
Super-plasticizer (kg/m ³)	8.27	8.27	8.27	8.27	8.27	8.27

2.3 Testing

The tests for the compressive and flexural strength were performed as per the American Society for Testing and Materials (ASTM) standards. For the compressive strength the samples were tested on day 28 for each mix with a loading rate of 1200 N/s according to ASTM C109/C109M–16a. The arithmetic average was calculated for each test. Three beams prism 40 × 40 × 160 mm³ of each mix were tested (according to the ASTM C 348-18 standard) for their flexural strength and tested on the 28 day with a loading rate of 2640 ± 110 N/min and 100 mm space between supports.

To measure the thermal conductivity of the samples a test was carried out on the flexural sample's fragments. To ensure no water moisture in the samples, samples were heated for 48 h in an oven at 60 °C. A Hot-Disk 2500 s thermal analyzer by the 5465 Kapton sensor disk with a radius of 3.189 mm was used to initiate the test. This analyzer measures the thermal conductivity, volumetric heat capacity, and thermal diffusivity with the use of transient plane source technique according to ASTM D7984 [22]. Each side of the sensor was covered by one sample of 40 mm thickness from each mix. An electric current passing through the sensor, generated heat that is then transferred to the samples. The rate of transfer is mostly dependent on the thermal properties of the mixture [23]. Each mix deign was tested for five minutes, twice, and

each time the analyzer was executed three times and thus, six values were obtained for each mixture design.

The printability test was conducted using a lab scale set up. This setup was made of an ABB IRB 140 six axis robot that handles a payload of 6 kg with an 810 mm range reach. A Putzmeister P12 mixer-pump with the ability to pump cementitious material with 4 mm particle size was used. This mixer-pump is able to pump in with two different pumping rate, namely 6 or 12 l/min, and has mixer drum with a capacity of 50 L. A 4 m pipe with a 25 mm diameter was used to deliver the concrete from the pump to the nozzle. The nozzle was round with a 20 mm diameter. After various trial tests, a print speed of 200 mm/s was used.

3 Results and Discussions

3.1 Unit Weight

The effect of replacing the natural aggregate by the EP on the unit weight of the concrete are shown in Fig. 2. As shown when the EP aggregate is not present in the mixture, the unit weight is approximately 2270 kg/m³. When EP ratio increased by 20 vol.-% consecutively, the unit weight decreased approximately at a linear rate. The unite weight of mixture EPC100 becomes 1700 kg/m³.

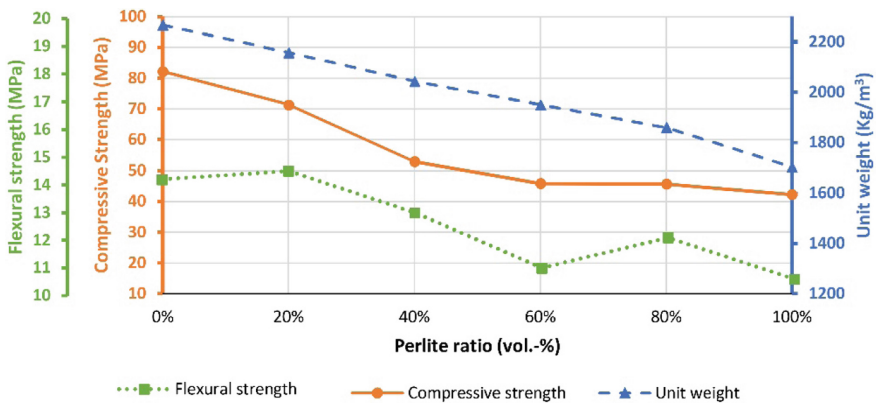


Fig. 2. Effect of Expanded Perlite on the unit weight, compressive strength, and flexural strength

3.2 Compressive Strength

For the sake of this discussion, the mixture NC (with 0 vol.-% EP) will be considered as the reference mixture. Figure 2 shows the results of the compressive strength testing on day 28. It is important to note that there was a non-linear decrease in compressive strength as the amount of EP in the mix increased. It was also observed that the highest

compressive strength, 82.17 MPa, was seen for the reference mix. The main observation from this i.e. the decrease in compressive strength as EP amount increased can be explained by the low compressive strength of EP which is as a result of its porosity. Thus, as EP replaces more sand, the compressive strength inherently decreases. Even though there was a reduction in the compressive strength of the mixture as more EP was added, the result obtained was still acceptable and comparable to that of 3D printing concrete mixtures in terms of strength.

3.3 Flexural Strength

Figure 2 clearly depicts the flexural strength measurements for the six mixtures when they were tested on the 28th day. Reduction in the flexural strength of the concrete from 14.2 MPa at 0 vol.-% EP in the reference mix to 10.6 MPa when 100 vol.-% of the sand is replaced with EP.

3.4 Thermal Conductivity

The thermal conductivity of a material refers to the measure of its ability to transfer heat. One of the major factors that affects the thermal conductivity of concrete is its porosity, mostly because the pores are filled with air and the low thermal conductivity of air affect that of the concrete. When EP replaces normal aggregates, the porosity of the concrete is increased and correspondingly the thermal conductivity is reduced too, in the process, the thermal insulation of the concrete is increased. This is validated by Fig. 3, which outlines the thermal conductivity of all six mixtures after they were tested. When the concrete aggregate was replaced with EP, the thermal conductivity reduced from 1.9 W/mK for mix NC to 0.69 W/mK for mix EPC100, A desirable 62% decrease in thermal conductivity was seen at the end of this experiment.

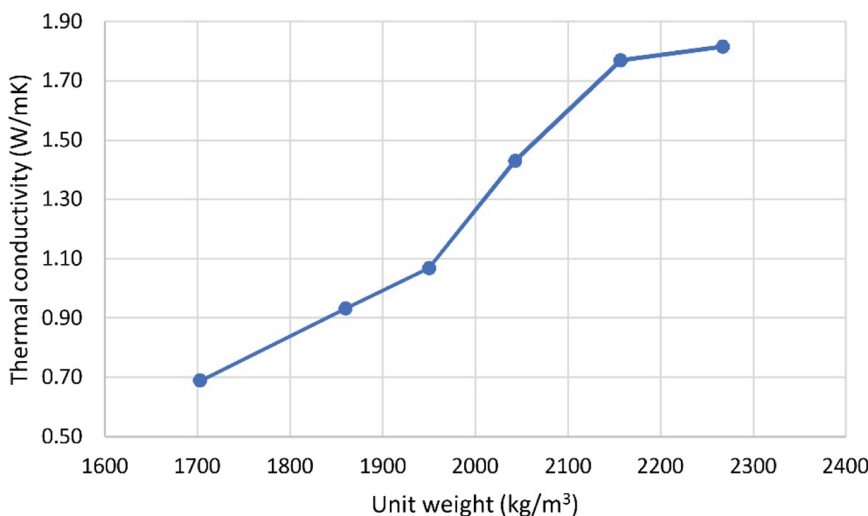


Fig. 3. Results of the thermal conductivity test

3.5 Printing Results

The printability of the mixtures was tested for preliminary evaluation using the mentioned setup in previous section. Mixture EPC100 with 100 vol.-% EP aggregate exhibited good printability characteristics with the aid of the accelerator admixture to control the setting time. Figure 4 illustrates the printing process of a rectangle with 30 cm $\times$ 40 cm sides to evaluate the printability of the developed concrete mixture.

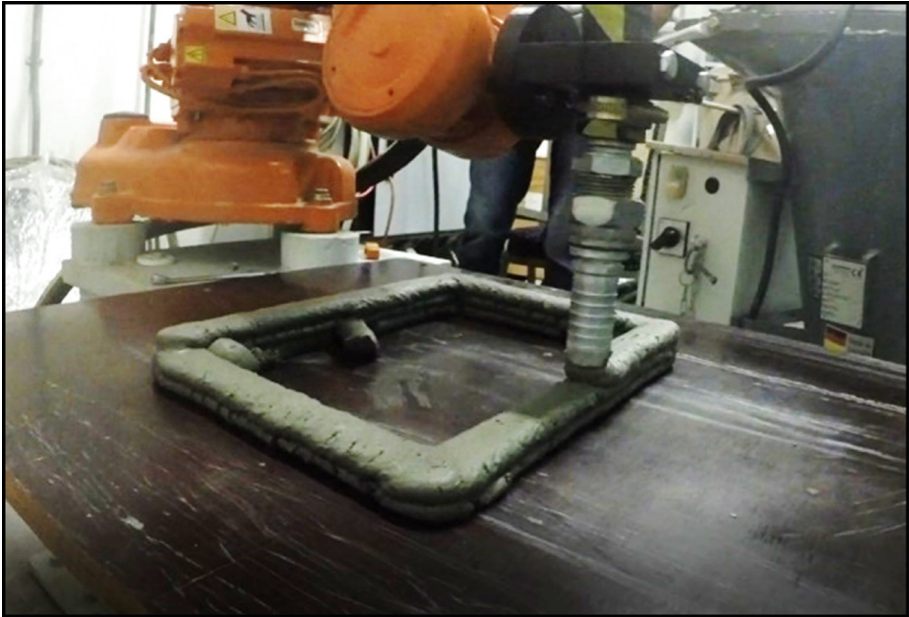


Fig. 4. Printability evaluation of mix EPC100

4 Conclusion

This paper has presented the effect of incorporating Expanded Perlite aggregate in high performance concrete. As the results showing the compressive strength and the flexural strength are decreasing as the percentage of EP increase within the concrete mixture. The reduction percentage of thermal conductivity is 62%, while it is 49% and 26% for the compressive and flexural strength respectively. After all of this reduction still the concrete mix with 100 vol.-% of EP has 42 MPa compressive strength which is suitable for use in 3D concrete printing. The printability of light weight concrete with 100 vol.-% expanded perlite was tested by using small lab set-up. The results of the test indicate that this material is suitable in the 3D concrete printing technologies. Furthermore, because of the low thermal conductivity of this new proposed concrete, it shows better insulation properties, and this makes it extremely beneficial for use in building construction and reduce the energy requirement for HVAC systems for heating and cooling. This can also

aid in reduce the environmental impact of the built environment in the operational phase. Further investigation is needed to determine the full-scale use of this material in 3D printing technology.

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Mechanical Characterization of Layer-by-Layer Interface in Concrete Elements Obtained by Additive Manufacturing

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Abstract. The anisotropic behavior of the 3D concrete printing elements represents a crucial key feature to be closely investigated. It is mainly due to the layered extrusion process, the most widespread digital concrete technology, which creates weak planes at the interface, known as “Cold Joints”, by placing material layer upon layer. To investigate the interface bond failure mechanism, the bond strength at the interface between layers was measured in this study, especially with respect to printing time gap between layers. In particular, this work provides a characterization of the mechanical properties of 3D printed concrete elements’ interfaces through the design and the implementation of an experimental setup supported by DIC technique, in order to study the shear behavior of layer interfaces. The study investigates different 3d concrete elements produced with 100 s, 200 s, 1800 s as time gap between layer deposition, showing a significant decrease in terms of maximum load up to about 50% for the elements realized with the higher value of resting time compared to bulk elements.

Keywords: Interface behavior · Concrete · Cold joint · 3D printing

1 Introduction

Concrete is actually the most widespread building material commonly used in engineering constructions, as it has excellent properties, such as low cost, general availability and good chemical and physical characteristics. The interest in the innovative methods for concrete elements production, such as Additive Manufacturing (AM) has grown dramatically, becoming a revolutionary technology areas also in construction industry [1–3]. Common concrete digital manufacturing technology is based on the concrete 3D printing system of Layered Extrusion [4], defined as the process of joining materials to create elements, layer upon layer, from 3D digital model, according to the definition given by the American Society for Testing and Materials (ASTM) International [5].

However, the implementation of this technology in practical cases of civil engineering is affected by numerous critical issues, such as the control of the material hardening over time or process dependent material properties. In fact, the time gap

between two deposited layers should be the shortest possible to ensure a maximum bond between two layers but long enough to have a self-sustaining element. Achieving a proper time gap that balances the two requirements mentioned above, determines a great relevance of the rheological properties of the fresh concrete material [6–8].

Moreover, the layered extrusion technology necessarily creates interfaces between subsequently deposited layers, namely “Cold Joint”. These surfaces might create a potential zone of weakness into the printed structures and depend on the time between the printing of two successive layers; in fact the bonding strength generally decreases with increasing the time [9].

Aside from the characteristics of the material, 3DCP (3D-concrete printing) process influences the behavior of the elements. Indeed, printed products show strong anisotropic behavior due to the presence of Cold Joints. This means that mechanical response of the printed elements depends on the direction of the loads compared to that of the joints [8, 10, 11]. Therefore, in the 3d concrete printing system, many components affect consistently the behavior of the elements, from material properties to geometry and printing path [12].

The present work focuses on the determination of mechanical properties of printed concrete elements and, in particular, on the characterization of the interface behavior between subsequent layers. In order to investigate the effects of the printing process on the mechanical properties of the elements, an experimental testing procedure is herein proposed. This investigation is aimed at assessing the effect of the resting time on the inherent strength of the interfaces and is based on a modified version of the punch-through shear test.

2 Materials and Methods

2.1 Printing Material

3D Printing process with concrete requires a fresh material characterized by specific parameters, as mentioned above, such as optimal viscosity and a high yield strength. The maximum aggregate size has to be compatible with the extrusion head whose nozzle has a diameter of 30 mm.

The cement-based mortar used in this study [14] was characterized by a low water/cement ratio of 0.38 for increasing the buildability of the material; a maximum diameter of the aggregates of 4 mm and short polypropylene fibers of 0.1% by weight, in order to prevent plastic shrinkage cracking in the early stage of curing and after the deposition stage. Nonetheless, because of the low water/cement ratio combined with the fibers, an admixture was needed to adjust the viscosity of such material. In particular, a polycarboxylate superplasticizer was added accordingly, achieving an optimal rheological balance, i.e. ensuring a good buildability along with a proper workability.

2.2 Printing Process

The aim of the experimental approach herein presented consists in determining the overall interlayer performances of the printed elements. Assuming the cold joints are

the weakest points of the printed elements, the study of the interfaces' behavior became a crucial issue to fulfill the structural requirements of any 3d printed concrete object.

3D printed specimens have been produced using BigDelta WASP printer, from the Italian CSP company [13], consisting in a triangular printing area, with sides of 4.0 m long, 3 braces connected to as many pillars and the printing head controlled by the braces that slide along the pillars, allowing exact positioning of the printing head inside the work area, as shown in Fig. 1 and Fig. 2.

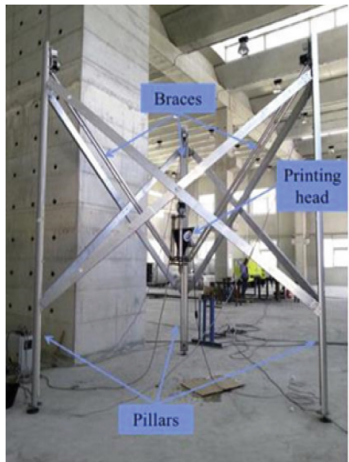


Fig. 1. BigDelta WASP printer.



Fig. 2. Printing process.

The printing head consists of a conical hopper capable of containing about 20 L of fresh concrete. A continuous movement of an endless screw towards the circular nozzle allows the extrusion of the concrete to precise flow speed. The overall print path is governed by a control unit and the numerous parameters, such as printing speed, flow velocity, height and thickness of subsequent concrete layers, are set in G-Code file, the input file for the 3D-printer.

2.3 Mechanical Characterization

The experimental activity is based on an experimental set-up similar to the Punch-through shear test proposed by J. Davies (1987) [15].

This test regards elements made of plain concrete and in particular is based on the idea of forcing a sliding fracture along two identified surfaces.

Nonetheless, some modifications to the original setup and the specimen's geometry due to constraints related to the printing process have been made; for instance the layers thickness cannot exceed some values imposed by the size of the nozzle and the consistency of the concrete.

The concrete samples were made of a total of 7 layers arranged in a way that 3 central layers are under the upper loading plate whereas the two external layers, on both sides of the sample, are in contact with the bottom supports (Fig. 3).

Even though the dimension of three layers is 60 mm, 1.5 mm on each side are left in order to compensate any geometric variability that may occur. Regarding to the side supports, one steel corner 5 mm thick is placed on each side of the specimen and fixed on the support plates using M6 screws. The dimensions and the details of the setup are reported in Fig. 3.

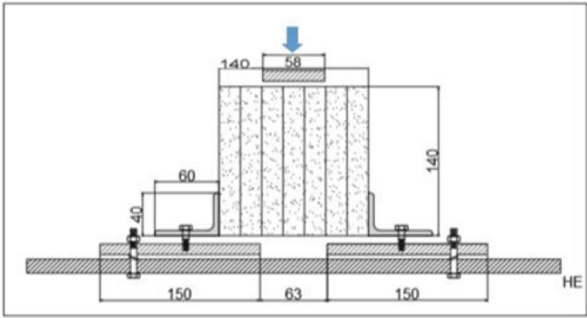


Fig. 3. Details of adopted setup.

2.4 Specimen Layout

In order to carry out the experimental tests prismatic specimens have been tested, compared with cast prismatic specimens.

Three different groups of specimens were printed, varying the waiting time. The waiting time t_r , i.e. the time that elapses between the printing of two subsequent layers, influences mostly the process of cold joints’ formation: higher is the waiting time, lower is the level of connection between layers. This is the reason why different waiting times ($t_{r1} = 100$ s, $t_{r2} = 200$ s, $t_{r3} = 30$ min) were selected in this study.

Furthermore, the single print has the flow speed parameter v in common. The overall characteristics of the 3 groups of printed specimens, in terms of dimensional properties (total height H, width W, height of each layer h and thickness d) and printing properties are summarized in the following Table.

Table 1. Main features of printed specimens.

Group	ID elements	H [cm]	W [cm]	h [cm]	d [cm]	Waiting time [s]	Printing speed [mm/m]
bulk	1_bk	14	14	2	5	100	2000
	2_bk						
	3_bk						
	4_bk						
A	A1	14	14	2	5	100	2000
	A2						
	A3						
	A4						

(continued)

Table 1. (continued)

Group	ID elements	H [cm]	W [cm]	h [cm]	d [cm]	Waiting time [s]	Printing speed [mm/m]
B	B1	14	14	2	5	200	2000
	B2						
	B3						
	B4						
C	C1	14	14	2	5	1800	2000
	C2						
	C3						
	C4						

2.5 Testing Procedure

The interlayer shear strength test was carried out by means of a servo-hydraulic universal machine, MTS810, under displacement control equipped with a linear variable displacement transducer, also commonly called LVDT, placed between the loading plate and the support girder.

To measure the strain of the specimens during testing, the Digital Image Correlation, DIC, techniques that employs tracking and image registration for accurate 2D and 3D measurements of changes in images, has been used. DIC works by comparing digital photographs of a component or test piece at different stages of deformation. A Matlab-based DIC code developed by Elizabeth Jones (2015) from University of Illinois at Urbana-Champaign [16] was used in this work.

An high contrast between the background and a random pattern of dots was needed, therefore the specimens' surface was firstly painted with a white non-acrylic paint and then a speckle pattern was applied on the same surface by using a simple black marker, as shown in Fig. 4. The images acquisition has been done by means of a high resolution camera, which records images every 2 s.

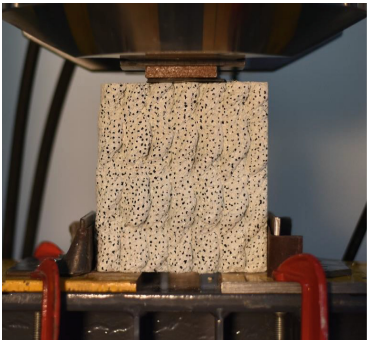


Fig. 4. Speckle pattern for interlayer shear test.

3 Results

The principal outcomes of the tests carried out on the plain (bulk specimen series in Table 1) and printed concrete elements are Load vs Displacement plots; more specifically, the vertical load, imposed by the MTS and measured by the load cell, and the vertical displacement of the loading plate evaluated by means of a vertical LVDT. In order to give a clear picture of the specimen's behavior, the plot (Load-Displacements), with regards to a bulk random sample, is shown in Fig. 5.

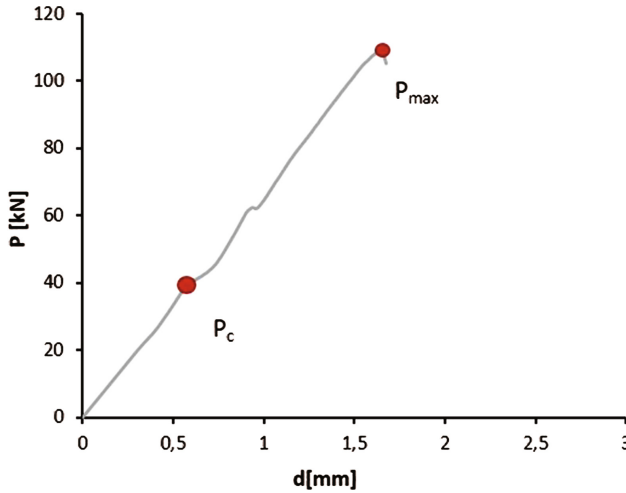


Fig. 5. Load-displacement plot of Plain Concrete element, 3_bk specimen.

Looking at the curve in Fig. 5, the specimen shows a behavior characterized by an initial linear branch until reaching a slight discontinuity which refers to the crack onset; afterwards, the loading starts again to increase up to the load that refers to the complete failure of the element.

The specimens have clearly exhibited a shear failure rather than a combination with flexural failure; specifically, the first cracks arose at the inner edge of the supports; subsequently the propagation of the fractures happens along the surfaces located between the supports and the loading platen. A confirmation of this type of failure is provided by the shear strain distribution achieved via the Digital Image Correlation (DIC). For instance, the distribution of the shear strains at the crack onset and at complete failure with regards to the specimen 3_bk are shown in Fig. 6.

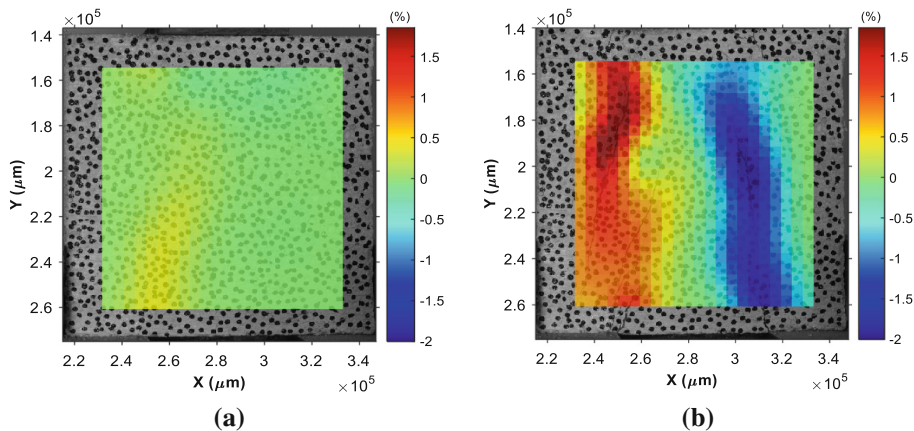


Fig. 6. **a.** γ_{xy} distribution at the crack onset, specimen 3_bk (point O); **b.** γ_{xy} distribution at the failure, specimen 3_bk (point F).

Against as an example in Fig. 7 the result of the tests on a random printed element is reported:

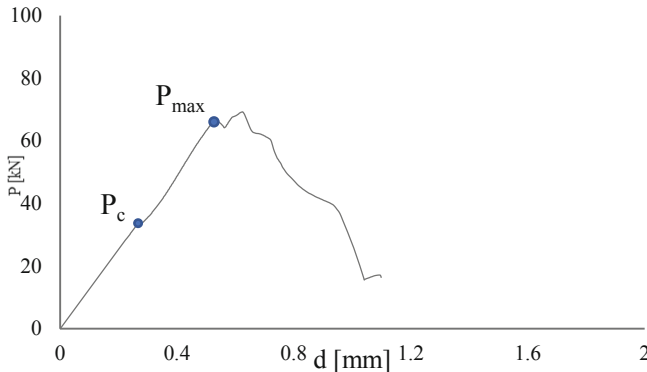


Fig. 7. Load-displacement plot, B4 printed specimen.

From the analysis of the results of printed specimens, the trend of the curves is about the same for every printed sample, characterized by two main stages, as in the case of bulk elements, but now the first linear part ends with the occurrence of a clear discontinuity that corresponds to the onset of the first crack in the interface surfaces and the relative load is called critical load, P_c . Subsequently, in the final part the load increases until its maximum value, P_{max} , which represents the complete propagation of the shear failure.

The graph in Fig. 8 shows a certain dissimilarity in terms of P_{max} values between the first two investigated groups of specimens (Series A and Series B), characterized by

similar waiting times, and the Series C. The same analysis does apply to P_c values of two groups, confirming that differences in the waiting time > 200 s imply appreciable differences in terms of reached load, weakening the printed element.

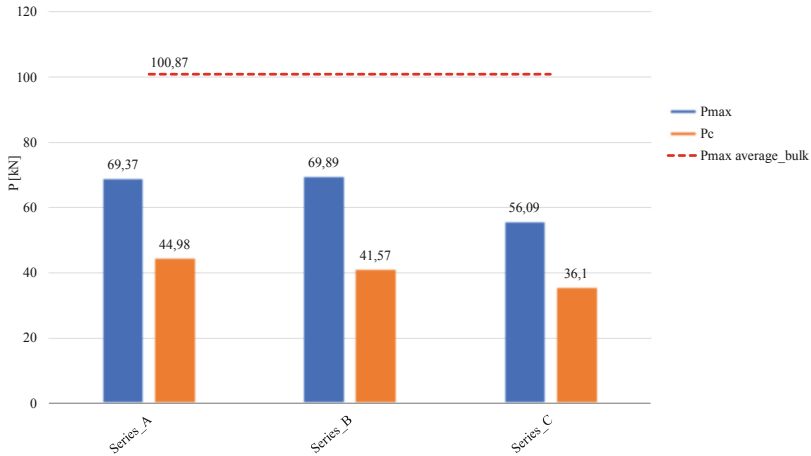


Fig. 8. Comparison between average values of P_{max} and P_c for printed samples.

Regardless of the waiting times, most of the printed specimens have exhibited a pure shear failure, i.e. vertical cracks have onset and raised in the vertical planes located in between of the inner edges of the supports and the load plate (see Fig. 9).



Fig. 9. Breaking behavior exhibited by the printed elements from a frontal and cross perspective

The presence of such failure mechanisms highlighted by the trend of the curves is also confirmed by DIC technique, which exhibits homogeneous strain distribution and consistent with the purpose of the test, i.e. producing a pure shear failure across the prefixed surfaces of fracture.

In the following figure, the shear strain distribution at the crack onset and at the failure for a random printed specimen belonging to group C is represented (Fig. 10).

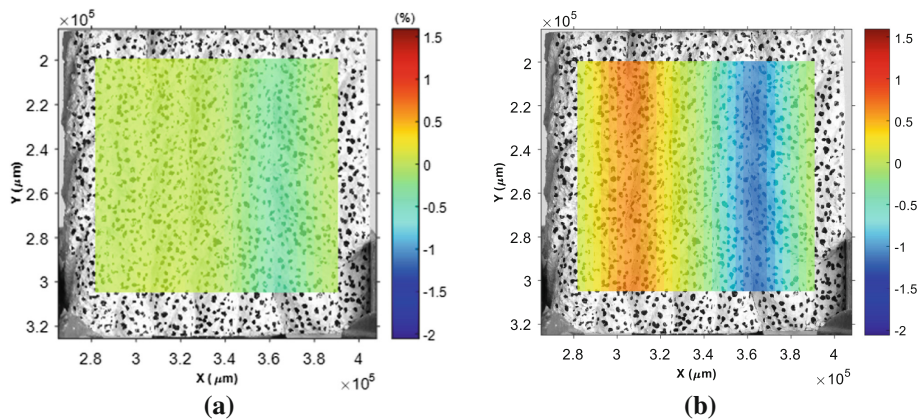


Fig. 10. a. γ_{xy} distribution at the crack onset, C4 printed specimen; b. γ_{xy} distribution at the failure, C4 printed specimen

The results are summarized in the following table with regard to printed and bulk elements, in order to compare the values.

The experimental results, in terms of average shear load ($\mu P_{\max}$) and corresponding average displacement ($\mu \delta_{\max}$), show that the maximum shear load about the plain concrete elements is about 45% higher than the maximum load of layered elements (Table 2).

Table 2. Experimental results.

Group	Experimental results	
	$\mu P_{\max}$ [kN]	$\mu \delta_{p\max}$ [mm]
A	69,37	0,83
B	69,89	0,92
C	56,09	1,11
Bulk	100,87	1,39

4 Conclusions

In this study, an experimental procedure to assess the interlayer strength of 3D printed concrete elements is presented, varying the resting time between subsequent layers and comparing the results with plain concrete specimens having the same dimensions.

Specifically, an experimental set-up has been proposed to test the response of different printed elements in terms of failure mechanism and to analyze the layers interaction and different sets of specimens were printed, characterized by a waiting time of 100 s, 200 s and 1800 s.

The results from the tests carried out on the elements characterized by distinct layers have shown a strong drop in terms of maximum shear load compared to plain

concrete elements; they have exhibited a shear failure along the surfaces of layers junction, confirming that the layers interfaces are weakness zones, regardless the time gap between the deposition of the layers.

Acknowledgements. Authors want to acknowledge Eng. Colella Francesco and the entire technical staff of Structural engineering laboratory of the University of Naples Federico II.

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Dynamic Behaviour of Layered 3D Printed Concrete Elements

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Abstract. Recently, the interest in digital fabrication techniques, such as 3D concrete printing, has grown at a dizzying speed, but at the same time many critical issues are still wide-open. Weak strength at the bond interface of two concrete layers, also referred as cold joint, is one such critical task to be scientifically investigated, especially in dependence on waiting time parameter between layers. It is a topic very structural engineering sensitive, because of the loss of instability and durability due to the occurrence of interface failure.

The aim of this work is the study of the effect of interfaces on mechanical performance of 3D printed cementitious elements under dynamic loading conditions. In order to achieve this, an experimental campaign was performed on 3d printed concrete elements varying the time intervals between placements of subsequent layers, through high and medium strain rate tensile tests, using a Hydro-pneumatic machine and a Modified Hopkinson bar apparatus, respectively. The results exhibited a decrease in the dynamic interface tensile strength with the waiting time up to over 90% for a medium strain-rate of about 10 s^{-1} and over 20% for a high strain-rate.

Keywords: Mechanical properties · Weak interfaces · Dynamic loading conditions · 3D printing concrete

1 Introduction

The development of the digitalization of design and construction processes has increased exponentially in the past few years, setting the Additive manufacturing field as one of the driving factors of the new Industry 4.0. The demand for complex and light-weight shapes, integration of components, simplification, customization, more efficient use of natural resources, cost and time optimization has inevitably led to the emergence of 3D printing technology also in the construction sector [1–3], in order to develop digital manufacturing techniques in applying concrete.

In this context, the layer by layer deposition of concrete material proved to be the most appropriate technique, probably due to its procedure based on the more widespread production of polymeric elements [4], which consists in the continuous

extrusion of the material from a digitally controlled nozzle, layer upon layer, and in the chance of on-site construction applications [5].

The great advantages deriving from the use of 3D printing technology in the building field are undeniable, but critical issues are still unsolved such as problems concerning the interface strength between the printed layers. In fact, 3D Layered extrusion of concrete leads necessarily to the occurrence of interfaces between subsequently deposited layers, so-called “cold-joints”, considered as zones of weakness that could potentially compromise the structural stability and also the durability of printed elements [5].

The interlayer strength depends on a large number of processing parameters, such as time, temperature, kinematics, composition of overlay concrete etc., but different studies focused mainly on waiting time between layers [6–9], aimed to evaluate the behaviour of the interface points with the changes in the time intervals between placements of subsequent layers.

The mechanical characterization of “cold-joints” represents a great research challenge for the field of digital concrete, but its study is still limited. In this regard, the work of Feng et al. [10] is worth mentioning, where an experimental study on the characteristics of a 3D printed layered cementitious material and FE modelling on the effect of construction process on the structural behaviour was presented, confirming that the resulting components from all extrusion-based processes are likely strongly anisotropic. A further analyse on mechanical behaviour of 3D printed concrete was performed by Wolfs et al. [11], through an experimental and numerical model, considering early age compression and shear properties of the fresh concrete. Nevertheless, a specific focus on the interfaces’ behaviour of 3D printed concrete elements is not available in the scientific literature.

So far, no dedicated approaches were reported on the bond of interface between 3D printed layers to examine its dynamic characteristics, at different strain-rate levels, with respect to static conditions.

The paper is organized as follows. First, a brief description of materials and printing process is presented. In Sect. 3 the adopted setup for the dynamic tensile tests and the examples of structural elements produced with 3D printing are given. The obtained results are discussed in Sect. 4 and finally in Sect. 5 a few concluding remarks are drawn.

2 Research Significance

Due to the recent advancements at a dizzying speed in additive manufacturing, the growing attention to the mechanical properties of the 3D printed elements represents a direct consequence. In addition, the evaluation of the capacity of the structural and non - structural printed components of achieving required performances, as its response to the seismic event, translates into the assessment of the interlocking effect on the dynamic behavior.

The main goal of this paper is to enhance the knowledge of the interface’s characteristics on the strength of elements resulting from 3D concrete printing (3DCP), when subjected to severe dynamic loads.

3 Materials and Methods

The experimental campaign on elements made of a proper cementitious material has been implemented. Different sample manufacturing techniques have been used: the traditional cast process, where concrete material is poured into formwork and then allowed to solidify, and the extrusion-based 3D-printing application, where the material is deposited layer-upon-layer without using mold.

3.1 Material Composition

3DCP mix design choice is the most important issue for defining concrete as a material able to reach the feasibility of 3D printing method. Specifically, the material must be designed to fulfil certain target rheological properties for describing its fresh-state structural build-up and performance requirements for hardened state [12, 13] and for satisfying the extrudability and buildability properties [14, 15].

The adopted material, the cement-based mortar, guarantees an optimal rheological balance and is reported in the work of Asprone et al. [4]; the open time is approximately 30 min during which the material can be extruded from the printer.

3.2 Specimen Preparation by Printing

For defining dynamic tensile behavior, an experimental campaign was carried out, characterized by two tests at medium and high strain-rates, on cylindrical specimens made of two layers with thickness of 10 mm each and diameter of 20 mm (see Fig. 1). The cylindrical samples were extracted from longer prismatic printed samples by a coring application and avoiding potential vibrations.

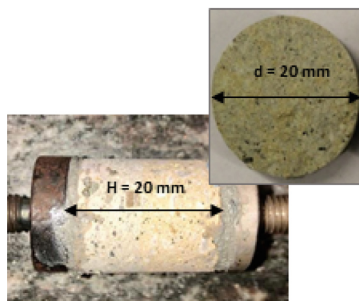


Fig. 1. Size cylindrical specimen

The relative thickness of the different layers is highlighted by the relative colors, created through the use of special pigments. This artifice has also been practiced to make the failure surface more evident during the tensile tests.

Specifically, three batches of three layered specimens were prepared. Each batch is characterized by the same material specifications above-described and by different time

intervals T_s between depositions of two subsequent layers ($T_s = 0$ min, $T_s = 10$ min, $T_s = 30$ min). These specimen groups were compared with another reference group, defined as bulk hereafter, made of cast material and tested in both static and dynamic conditions. The total number of specimens used for shear characterization was of 36 specimens. The Table 1 shows clearly the labels given to each sample.

Table 1. Specimen labels.

		Bulk	T0	T10	T30
Static tensile test	$(\dot{\epsilon} = 10^{-5} \text{ s}^{-1})$	2L_001	2L_T0_001	2L_T10_001	2L_T30_001
		2L_002	2L_T0_002	2L_T10_002	2L_T30_002
		2L_003	2L_T0_003	2L_T10_003	2L_T30_003
Dynamic tensile test	medium strain-rate $(\dot{\epsilon} = 50 \text{ s}^{-1})$	2L_001m	2L_T0_004m	2L_T10_004m	2L_T30_004m
		2L_002m	2L_T0_005m	2L_T10_005m	2L_T30_005m
		2L_003m	2L_T0_006m	2L_T10_006m	2L_T30_006m
	High strain-rate $(\dot{\epsilon} = 200 \text{ s}^{-1})$	2L_001h	2L_T0_004h	2L_T10_004h	2L_T30_004h
		2L_002h	2L_T0_005h	2L_T10_005h	2L_T30_005h
		2L_003h	2L_T0_006h	2L_T10_006h	2L_T30_006h

The prismatic specimens were prepared using a WASP printer produced by Italian CSP Company [16]; the printer, of which a clear plan is reported in [4], consists of 3 braces sliding along many pillars and controlling the printing head, made of a conical hopper in which the fresh concrete is pumped and extruded through circular nozzle of 25 mm diameter. The printing input parameters include: the concrete layer height (approximately 12 mm), the printing speed (deposition rate) assumed equal to 2000 mm/m and the screw flow of 360 rad/s.

3.3 Experimental Set-up for Static and Dynamic Tests

The entire experimental campaign, in both static and dynamic loading conditions, was performed in the DynaMat Laboratory of the University of Applied Sciences and Arts of Southern Switzerland. The mechanical response of specimens was assessed after 28 days of curing in open air and at room temperature.

Tensile failure tests were performed in according to European Standard EN1015-11 [17] using a universal servo-controlled machine with a constant strain-rate of 10^{-5} . Ordinary conditions, in terms of humidity and temperature, were adopted for conducting the tests. Quasi-static tests were performed by means of a universal electro-mechanical testing machine type Zwick/Roell-Z50 (maximum load capacity of 50 kN). A bi-component epoxy resin was used to glue the specimens to the supports. The required hardening time at room temperature is at least 8 h.

The main aim of tests under static conditions was to have reference data for the dynamic characterization. For investigating dynamic tensile behaviour, two different experimental setups were implemented. For medium and high strain-rate tests a

Hydro-Pneumatic Machine (HPM) and a Modified Hopkinson tensile Bar (MHtB) were used respectively.

The HPM is made of a cylindrical tank divided by a sealed piston in two chambers, filled with gas at high pressure (e.g. 150 bars) and water. The test starts when the equilibrium between two chambers is changed, i.e. the second chamber discharges the water through a calibrated orifice, activated by a fast-electromagnetic valve. Then, the piston starts moving expelling out the gas through a sealed opening, whose end is connected to the specimen; the specimen is linked to the other extremity to an elastic bar, rigidly fixed to the structure supporting the machine. When the piston shaft moves, the specimen is pulled at a constant velocity, depending on the velocity of the water expelled from the chamber that is function of the diameter of the circular orifice placed at the chamber exit. The crack opening displacement was directly measured following the motion of two black and white targets painted on the bar ends, closer to the specimen (see Fig. 2a).

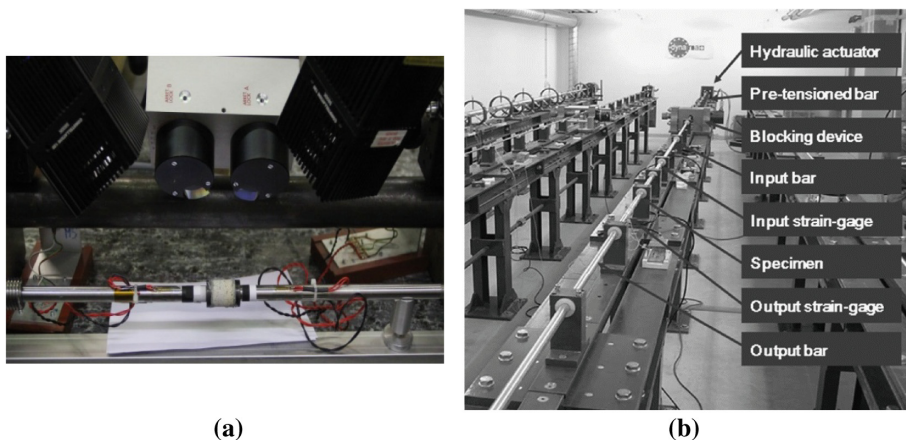


Fig. 2. a. Hydro-pneumatic machine for medium strain-rate tests; b. Modified Hopkinson tensile Bar apparatus

An electro-optical extensometer Rudolph 200XR with a measuring range of 5 mm (maximum resolution of $5 \cdot 10^{-4}$ mm) and equipped by a gauge length adapter (1–25 mm) was used. More details on the functioning of HPM can be found in different works [18–21]. Whereas a Modified Hopkinson tensile Bar (MHtB) apparatus was used to conduct high train-rate tests (see Fig. 2b).

The machine consists of two longitudinally aligned aluminum bars 20 mm in diameter, the namely input bar and output bar, characterized by front and end surface contact, between which the specimen –with the same diameter as the input and output bar– is connected by using a bi-component epoxy resin. The input and output bars were

instrumented with semiconductor strain gauges that measure the incident, reflected and transmitted pulses acting on the cross section of the specimen. The pre-tensioned bar was a high strength steel directly connected to the input bar.

The functioning scheme consists in: firstly a hydraulic actuator pulls end of the pre-tensioned bar, which is jammed on the other end by the blocking device. The pulse propagates along the input bar. When the incident pulse (ϵ_I) reaches the specimen, one part (ϵ_R) is reflected by the specimen and another part (ϵ_T) passes through the specimen propagating into the output bar. The amplitudes of the incident, reflected and transmitted pulses depend on the mechanical properties of the specimen. Strain-gauges placed on the input and output bars measure the elastic deformation created on both bars, respectively, by the incident/reflected and transmitted pulses [19, 22].

4 Results and Discussion

Tensile test data processing can be used to investigate the behavior of the plain and printed concrete subjected to a dynamic regime, at different strain rates. The strain rate during the test is not a constant value, but varies with time so its definition becomes complicated.

The imposed strain-rates, equal to the ratio between strain velocity and initial specimen length, are calculated:

$$\dot{\epsilon} = \frac{v_s}{L_0} \tag{1}$$

In the following table, the values of imposed strain-rates in the tests are reported (Table 2).

Table 2. Imposed strain-rates in the tests.

v_s [m/s]	L_0 [m]	$\dot{\epsilon}$ [s ⁻¹]
0,000002	0.02	10 ⁻⁵
1		50
4,316		215

These results have been compared with the static performances, reported in terms of numerical values in Table 3. Furthermore, in the static tensile loading condition, a notch into the bulk specimen, in correspondence with the layer surface, has been produced, in order to induce the tensile crack in the middle of the specimen.

Table 3. Tensile failure tests results

Loading conditions	Resting time (min)	$F_{\max, \text{ave}}^*$ (N)	$\sigma_{t, \text{ave}}^*$ (MPa)	$\sigma_{t, \text{st dev}}^*$ (MPa)	Static series variance (%)	Fracture time (s)
$\dot{\epsilon} = 10^{-5} \text{ s}^{-1}$	Bulk	566	3,15	1,2	–	29,1
	0	415	1,34	0,3	–	15,0
	10	144	0,46	0,3	–	10,4
	30	364	1,03	0,2	–	21,5
$\dot{\epsilon} = 50 \text{ s}^{-1}$	Bulk	992	3,16	0,5	0%	8,5E–03
	0	1293	4,19	1,3	68%	5,1E–03
	10	491	1,59	1,0	71%	2,2E–03
	30	510	1,65	0,1	38%	6,7E–03
$\dot{\epsilon} = 200 \text{ s}^{-1}$	Bulk	2562	8,31	0,2	62%	3,6E–05
	0	2393	7,76	1,4	83%	3,9E–05
	10	1959	6,3	1,3	93%	3,0E–05
	30	1084	3,51	0,5	71%	2,9E–05

*Suffix “ave” and “st dev” indicate average and standard deviation values, respectively.

The fracture time is measured in correspondence with the maximum stress value, assumption justified by the fact that the mortar is characterized by a brittle-like behavior and so the onset of the first fracture is supposed correspond with the failure of the material.

A comparison between the different loading conditions, in terms of maximum normal stress exhibited by every specimen, with varying the waiting time, showed an increase in tension with the testing velocity and a decrease with time of waiting in the deposition of layers (see Fig. 3).

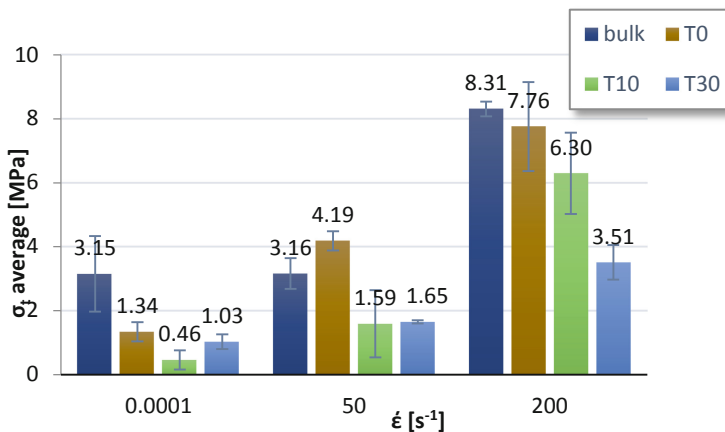


Fig. 3. Static series variance, in terms of tensile stress, at different strain rates

From the analysis of the specimens' response over time, it can be observed that, as strain-rate increases, the specimens reached the failure quickly, in correspondence of higher tensile strength (see Figs. 4 and 5). Accordingly, in the Table 3, the time to fracture for every strain rate reveals a marked reduction varying from lower strain rates to higher ones.

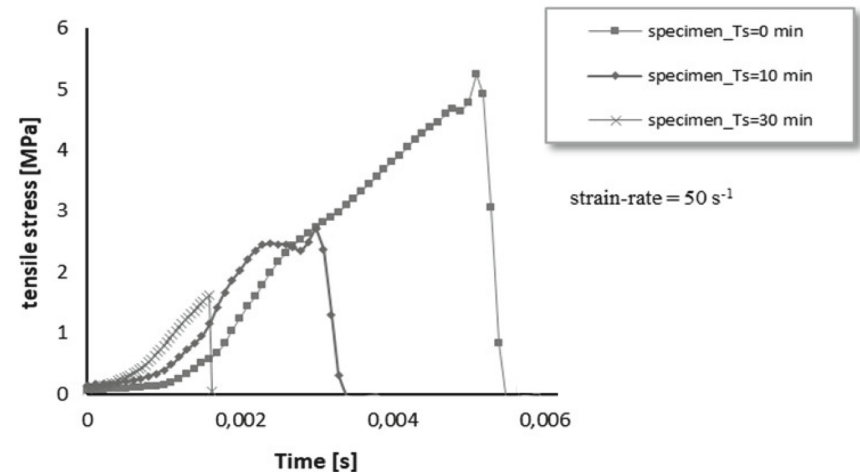


Fig. 4. Comparison between stress-time curves for specimens with different waiting times at medium strain rate

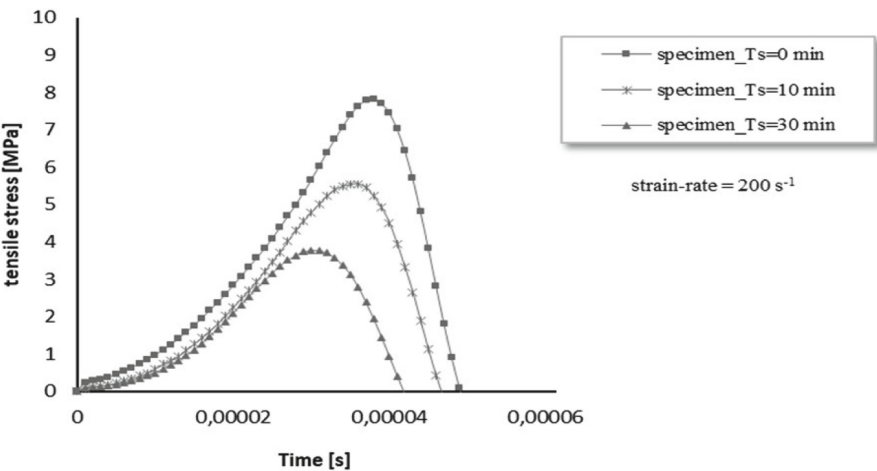


Fig. 5. Comparison between stress-time curves for specimens with different waiting times at high strain rate

Figure 6 and 7 show printed concrete specimens before and after its failure, subjected to high strain-rates. As it is already typically observed in normal concrete material, also in these types of elements a first crack develops approximately in the middle of the specimen length, defining a more or less clean cut at the cross-section according to more or less high waiting time between layers.

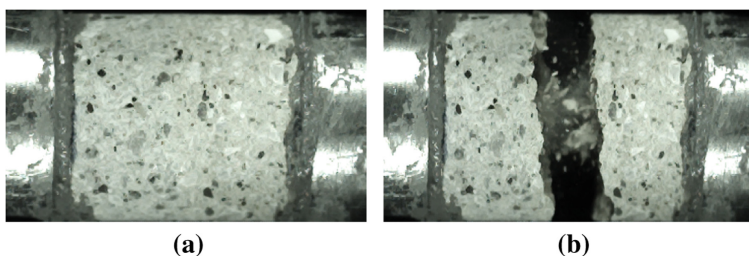


Fig. 6. a. Printed specimen with $T_S = 0$ min before high dynamic tensile test; b. Printed specimen with $T_S = 0$ min after high dynamic tensile test

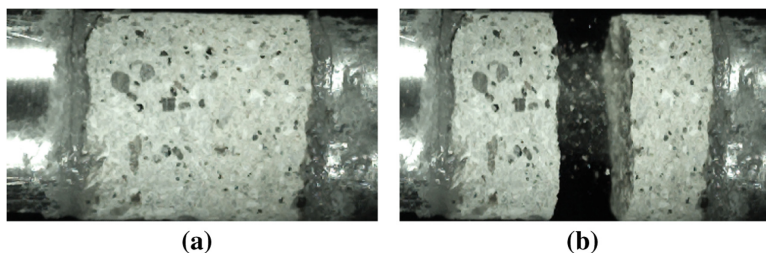


Fig. 7. a. Printed specimen with $T_S = 30$ min before high dynamic tensile test; b. Printed specimen with $T_S = 30$ min after high dynamic tensile test

5 Concluding Remarks

Due to the recent growing development of the digital technologies in the construction sector, the mechanical response of the extrusion-based 3D printed concrete elements, under static and dynamic loading conditions, and the relative effects of different delay time were investigated in this study. Reference tests leading static mechanical properties have been compared with tensile failure tests for analyzing the dynamic characteristics, on both bulk and printed material elements, with the change in the delay times.

The dynamic tensile tests were conducted using a Hydro-Pneumatic Machine for medium imposed strain-rates and a modified Hopkinson bar for high strain-rate. Experimental results revealed that the 3D printed elements, under high dynamic tensile condition (evidently the condition to which a layered element is more sensitive) present

a variation with respect to static conditions as waiting time increases, presenting a quasi-linear trend. Precisely, the reduction of tensile strength becomes significant starting from the waiting time reaches 30 min, showing a decrease of around 58% with respect to bulk material condition. Hence, it appears that the mechanical dynamic characterization needs to be conducted, in order to analyze the structural stability of printed elements under dynamic loads and investigate their vulnerability. Furthermore, the influence of waiting times on the mechanical properties requires an appropriate characterization, given its importance in the determining the main features of 3D printing process affecting the total behavior of the element. The knowledge of the consequences of the critical issues associated to the loss of strength at the interfaces, especially in the dynamic regime, guides the future research on the 3D printing limits towards the exploration of new frontiers.

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Characterizing the Fissility of 3D Concrete Printed Elements via the Cohesive Zone Method

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Abstract. This research examines the differential interlayer capacity of 3D concrete printed (3DCP) specimens via mechanical characterization procedures, comprising of direct tension test (DTT), Iosipescu shear test (IST), and orthogonal compression tests. The experimental findings are subsequently correlated to cohesive parameters that represent the adhesive capacity of the interfacial transition zone (ITZ). Furthermore, the cohesive parameters are validated via supplementary mesoscale analytical calibration and finite element (FE) analysis procedures. The experimental works conducted are envisioned to take an incremental step towards detailed design specifications that allow for the rational design of load-bearing 3DCP components and structures at a macroscale.

Keywords: 3D concrete printing · Material characterization · Numerical analysis · Cohesive zone modeling · Experimental testing

1 Introduction

The potential to employ advanced industrialized manufacturing techniques, such as 3D concrete printing (3DCP), in the construction industry, has provided a new paradigm for clients, designers, and contractors alike. With proposed advantages such as improved structural efficacy, reduced cost, optimum material usage, quality and safety improvements, as well as the possibility to construct custom geometries without the need for bespoke formwork solutions has attracted attention in the emerging digital construction era. The value added by this novel approach is set to revolutionize the construction industry, but will first have to surmount the current hurdles impeding its widespread adoption [1, 2].

Furthermore, the ability to conduct computational analysis procedures that accurately capture the response of 3DCP components under design loading conditions is paramount to the scalability and validation of 3DCP specific structural design techniques. Due to 3DCP operating within the additive manufacturing paradigm, the option to employ Classical Laminate Theory (CLT) for numerical analysis is investigated.

CLT is a conventional analytical means that facilitates the computation of multifaceted coupling effects of composites, such as layered concrete composites. Consequently, the experimental works presented seek to characterize the composite mechanical attributes prevalent in 3DCP components. The experimental data is utilized to numerically calibrate the required constitutive cohesive parameters required for cohesive zone modeling (CZM) computational analysis procedures. This is set to take an incremental step towards design specifications that facilitate the development of rational design procedures for load-bearing 3DCP components.

2 Materials and Experimental Methods

2.1 FRPC Constituents

A fiber-reinforced printable concrete (FRPC) mixture is employed containing the specific constituent fractions presented in Table 1. The mixture's grading is tailored to achieve maximum particle packing density and approximates Fuller's ideal grading [3]. Furthermore, continuously graded Malmesbury coarse aggregate with a 4.75 mm maximum particle size, accompanied by micro-silica fume and class F fly-ash extenders are utilized. The incorporated additives comprise a modified polycarboxylate polymer-based superplasticizer and a viscosity modifying agent (VMA). High modulus polypropylene (HM-PP) microfibers with the specific properties listed in Table 2 are entrained at a 1% dosage by volume. The mixture has a water to cement ratio of 0.45 and a 28-day compressive capacity of 78 MPa and can thus classify as a high-performance concrete (HPC) [4].

Table 1. FRPC mixture constituent quantities.

Constituent	kg
PPC Suretech CEM II/A-S 52.5 N	562
Durapozz Fly Ash (Class F)	162
Micro Silica Fume	81.4
Fine Aggregate (Malmesbury)	1144
Water	256
Superplasticizer	0.6% by binder mass
VMA	0.3% by binder mass
6 mm HM-PP Microfibres	1% by mixture volume

Table 2. High-modulus polypropylene (HM-PP) microfiber properties.

Description	Value
Young's Modulus (E_f)	30 GPa
Yield Stress (f_t)	1200 MPa
Diameter (d)	15 μ m
Length (L)	6 mm

2.2 Experimental Program

The experimental program presented seeks to characterize the composite mechanical attributes prevalent in additively manufactured 3DCP components. As extensively reported in the literature, 3DCP elements exhibit differential inter and intralayer matrix capacities [5–7]. This fissility can be attributed to a variety of interdependent material, fabrication process, and design parameters, which all, affect the mechanical performance of 3DCP parts [2]. Prisms are saw-cut from a 3DCP wall panel to ensure that the aforementioned interdependent parameters (i.e., layer height, print speed, nozzle standoff distance, print time interval, and climatic conditions) remain consistent. The material constituents required for the experimental program are batch mixed before commencing the trials, ensuring the reproducibility of the rheological properties of the FRPC.

The interlayer capacity and characteristics are assessed via direct tensile tests (DTT), Iosipescu shear tests (IST), and orthotropic compression tests, which collectively represent the composite interaction characteristics at a 28-day curing age. The cohesive parameters required to assess the respective Mode I (opening) and Mode II (sliding) interfacial failure mechanisms are obtained from the DTT and IST. All specimens are cured in a climate-controlled room (23 ± 2 °C and $65 \pm 5\%$ relative humidity).

Direct Tension Tests. The DTT's are performed on $40 \times 30 \times 60$ mm ($b \times d \times h$) samples, illustrated in Fig. 1. The DTT's are conducted perpendicular (Direction I) and parallel (Direction III) to the interlayer, respectively. The tests are performed under displacement control at a 0.25 mm/min rate in a 5 kN MTS material testing machine (MTM). The prisms are aligned, epoxy glued to symmetric T-sections, and cured for 5 days. The DTT's are conducted with fixed end constraints to ensure that no rotation is prevalent on the rupture interface, ensuring independent mode conditions are represented. Furthermore, a 3.5 mm mid-height notch (L_n), with a 1.75 mm tip radius, ensures a predictable failure plane. The notch depth is approximately 5 mm on either side of the specimen, rendering a notch width (b_n) equal to 30 mm.

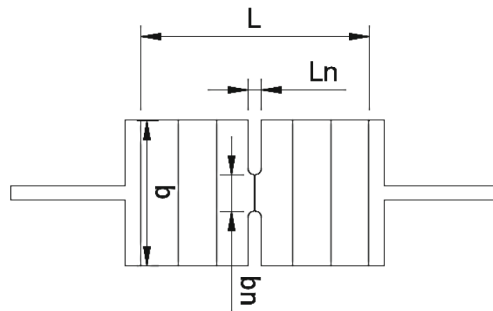


Fig. 1. DTT experimental setup illustrating the specimen geometry.

Iosipescu Shear Tests. The IST's are performed on $80 \times 30 \times 160$ mm ($h \times b \times l$) prisms in the experimental setup presented in Fig. 2a. The displacement-controlled tests are conducted in a Zwick Z250 MTM at a 0.25 mm/min loading rate. The tests are conducted with the induced loading orientated parallel and perpendicular to the ITZ. Figure 2a illustrates a 45° diagonally orientated LVDT situated over the shear plane allowing for high-resolution displacement and dilation readings to be attained. The specimen geometry is dictated by the ratio of shear-stress to flexural stress at the critical locations depicted in Fig. 2b. Equation (1) presents the shear/moment relationship that is set to 2, ensuring that Mode II failure dominates. Figure 2b illustrates the elastic shear stress distribution over the notched region; thus, an average shear stress distribution is assumed. To satisfy the relationship above a notch height (h_n) of 20 mm is required and the distances (a) and (L) in Fig. 2c is 30 mm and 110 mm, respectively.

$$\frac{\tau}{\sigma} = \frac{V}{h_n b} \bigg/ \frac{Mh}{2I} = 2.0 \quad (1)$$

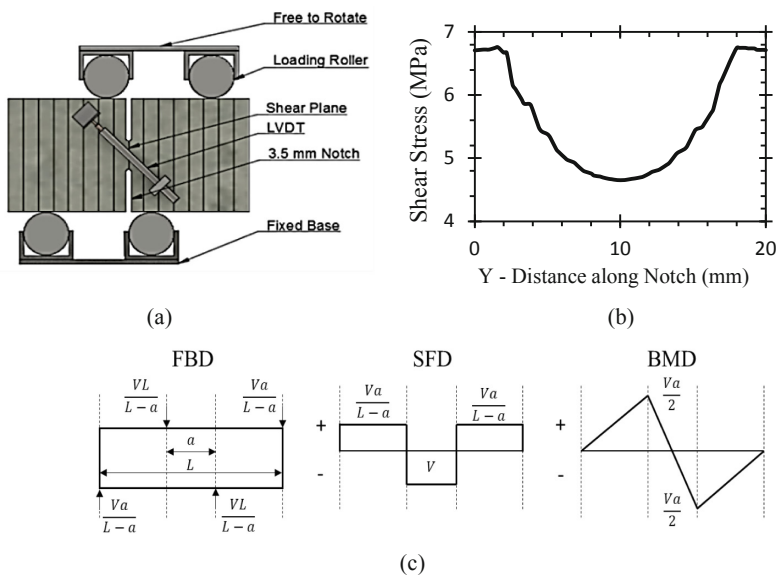


Fig. 2. (a) Iosipescu shear test setup, (b) depicts the elastic shear stress distribution over the notched region, and (c) the free-body diagram (FBD) indicating the applied loading in terms of the shear force (V), the shear force diagram (SFD), and the bending moment diagram (BMD).

Orthotropic Compression Tests. The orthotropic compression capacity of the FRPC mixture is evaluated perpendicular and parallel to the ITZ, as illustrated in Fig. 3a. For

direction I, $40 \times 30 \times 40$ mm prisms are extracted from printed samples and tested. For direction III, residual prism halves from four-point flexural tests are centered relative to $40 \times 40 \times 5$ mm auxiliary steel platens, which provide a means to determine the compressive area. A minimum of 5 samples per loading direction is tested. Additionally, 40 mm^3 mold cast samples are evaluated to obtain the compressive

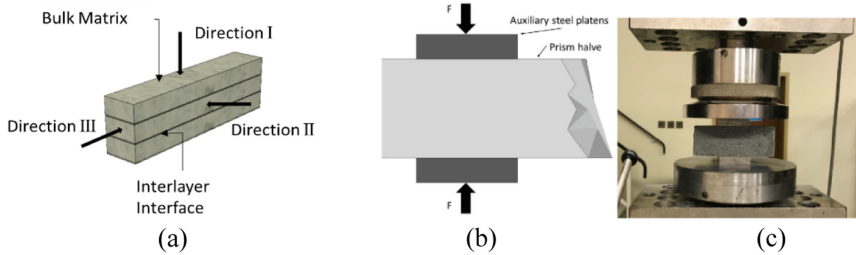


Fig. 3. Experimental test setup for the orthotropic compressive test, (a) illustrates the respective loading directions, (b) the steel platens employed, and (c) the Zwick Z250 MTM and a visual depiction of the experimental setup.

capacity of the non-pumped concrete matrix. All samples are tested in a Zwick Z250 MTM under load control at a 2400 N/s rate.

3 Results and Discussions

3.1 Direct Tensile Tests

The DTT results are presented in Fig. 4 and summarized in Table 3. Note that the slight non-linear ascending portion in the $F-\delta$ response is ascribed dominantly to

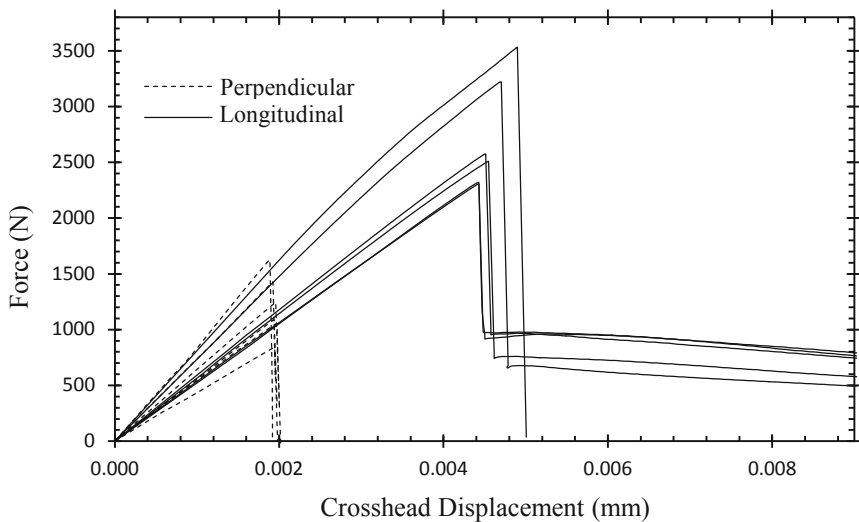


Fig. 4. Experimental direct tensile results at a 28-day curing age normal to the interlayer interface.

Table 3. Summary of direct tensile test (DTT) results.

		S1	S2	S3	S4	S5	S6	Avg	CoV
Perpendicular to the interlayer transition zone (ITZ) - Direction I									
F_{break}	N	1245	1053	841	1627	1428	1089	1214	23%
t_0	MPa	1.41	1.20	0.96	1.79	1.71	1.30	1.40	22%
δ_{break}	μm	1.96	1.97	1.95	1.89	1.92	1.94	1.94	2%
Parallel to the interlayer transition zone (ITZ) - Direction III									
F_{break}	N	2306	2508	2575	3221	2319	3531	2743	19%
t_0	MPa	2.63	2.61	2.60	3.13	2.29	3.52	2.80	16%
δ_{break}	μm	4.43	4.55	4.51	4.70	4.43	4.90	4.59	4%

frictional slip. Subsequently, δ is adjusted based on linear elastic theory to eliminate this effect. For the FRPC utilized, an average interlayer tensile capacity of 1.4 MPa is observed. The longitudinal direction displayed an average tensile capacity of 2.8 MPa, with an average post-peak capacity of 0.9 MPa. In both instances, the tensile failure mechanism manifests as a single hairline fracture over the notched region. Considering the results, it is evident that a frail brittle interlayer interface exists in 3DCP elements.

3.2 Iosipescu Shear Tests

The IST results are presented in Fig. 6 and summarized in Table 4. The results indicate that the ITZ has an average shear capacity of approximately 3 MPa loaded parallel to the ITZ, and a 2.4 fold greater capacity when loaded transversely. On the ITZ, Fig. 5a, brittle post-peak behavior is prevalent, followed by a slight residual shear capacity of 0.2 MPa. During the IST a second shear-flexure failure mechanism is observed, where

Table 4. Summary of Iosipescu shear test (IST) results.

		S1	S2	S3	S4	Average	CoV
Parallel to interlayer transition zone – Direction III							
F_{break}	N	1811	1701	1703	1886	1775	5%
t_0	MPa	3.02	2.84	2.84	3.14	2.96	5%
δ_{break}	mm	0.072	0.070	0.071	0.073	0.071	2%
Perpendicular to interlayer transition zone – Direction I							
F_{break}	N	4200	3983	4470	–	4218	6%
t_0	MPa	–	–	–	–	7.20*	
δ_{break}	mm	0.165	0.223	0.151	–	0.180	21%

* an equivalent representation, since the failure plane dimensions where irregular.

the shear fracture plane deviates from the interlayer interface towards the lower right loading roller adjacent to the notch (refer to Fig. 2a) resulting in a more ductile shear

softening behavior. This is likely due to slight imperfections on the loading surface, resulting in an uneven load distribution.

The results pertaining to the transversely loaded specimens depict a parabolic failure mechanism that propagates away from and back to the notched region as shown in Fig. 5b. This mechanism is a result of the lower interfacial shear capacity therefore



Fig. 5. Predominant shear failure mechanisms, (a) interfacial pure shear failure, and (b) combined shear-flexure failure.

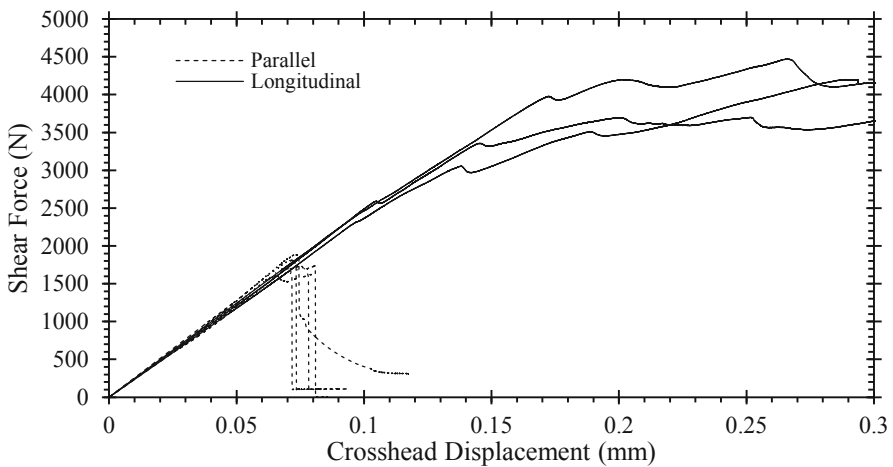


Fig. 6. Experimental shear test results at a 28-day curing age normal to the interlayer interface.

the crack path favors the interlayer opposed to traversing the matrix. When the crack tip deviates away from the zero moment position flexure dominates, consequently the crack path returns to the notched region. Therefore, the shear capacity cannot technically be expressed in terms of stress, but is estimated at 7.2 MPa for a vertical crack.

3.3 Compression Tests

Table 5 presents the average compressive strengths of the cast and printed specimens in the respective loading directions. Anisotropic compression capacities are observed,

where the compressive strength in Direction III exceeds that of Direction I. This is consistent with the experimental works presented for FRPC's, where the laminates

Table 5. Average compressive strength at a 28-day curing age.

		f_{cu}	CoV
Direction I	MPa	39.65	7%
Direction III	MPa	44.72	11%
Cast (Matrix)	MPa	77.9	3%

anisotropy is due in part to the orientation of the smearing layer, the extrusion pressure, and the extrusion direction [8]. The large variation between the cast and printed specimens, can likely be ascribed to a greater air void ratio in the ITZ and water curing of the cast samples. However, subsequent investigation is required.

4 Analytical and Numerical Calibration

4.1 Analytical Calibration

As presented in Sect. 3, the DTT method employed is subject to additional elastic deformation of the matrix above the notched region. Therefore, the interlayer characteristics are not sufficiently captured due to snap-back occurring after the interlayer capacity has been exceeded. Equation (2) presents an expression for the lengthening (δ), assuming exponential softening and uniform stress distribution of the cracked region. Consequently, Eq. (3) presents an analytical means for calculating the minimum fracture energy (G_f) required to prevent snap-back, which implies that, just beyond the peak tensile resistance of the specimen the onset of softening in the $F-\delta$ response must have a negative slope ($d\delta/dF < 0$). Substituting the geometric and material parameters presented in Sect. 2 and the pre-shifted cohesive element stiffness (E_{nn}) equal to $5 \times 10^9 \text{ N/m}^3$, the minimum G_f is found to be $G_f > 398.1 \text{ N/m}$. Such an excessive energy requirement validates that snap-back occurs. This low cohesive zone stiffness accounts for MTM test chain elasticity and slip in the clamps. If MTM elasticity and slip are excluded, a proportionally high value of E_{nn} is justified, which effectively reduces the third term in brackets of Eq. (3) to zero. This produces $G_f > 4.8 \text{ N/m}$ in Eq. (3), which is less than the expected 100 N/m for concrete in tension and is thus selected as the E_{nn} for the FE analysis.

$$\delta = \frac{F(L - L_n)}{btE} + \frac{FL_n}{b_ntE} \frac{\kappa + 1}{2} + \frac{F}{b_ntE_{nn}} - \frac{G_f}{f_t} \ln\left(\frac{F}{f_t b_nt}\right) \quad (2)$$

$$G_f > \left[\frac{(L - L_n)}{btE} + \frac{L_n}{b_ntE} \frac{\kappa + 1}{2} + \frac{1}{b_ntE_{nn}} \right] f_t^2 b_nt \quad (3)$$

4.2 Finite Element Analysis

In this section, an Abaqus CAE 3D Standard/Implicit static finite element (FE) analysis

Table 6. Numerical finite element simulation parameters.

Elastic parameters			
E	32 GPa	ν	0.2
E_{nn}	$1 \times 10^{15} \text{ N/m}^3$	$E_{ss/tt}$	$1 \times 10^{15} \text{ N/m}^3$
Damage parameters			
t_{nn}	1.4 MPa	$t_{ss/tt}$	3 MPa
G_{fnn}	100 N/m	$G_{fss/tt}$	150 N/m

is implemented to simulate the DTTs presented in Sect. 2. The numerical analysis utilizes the material parameters given in Table 6, in addition to 10 μm thick 8-node 3D cohesive (COH3D8) and 3D stress (C3D8R) elements with an element mesh size of 2 mm. An over meshing factor of five is applied to the COH3D8 elements. The analysis is determined to be mesh independent under the uniaxial loading conditions applied.

Furthermore, the maximum stress (Maxs) traction-separation damage initiation criterion is implemented, accompanied by an energy-based Benzeggagh-Kenane mixed-mode fracture criterion with exponent (n) equal to one. Resulting from the relatively low expected stresses adjacent to the notched region elastic behavior is assumed.

Finite Element (FE) Analysis Results. The results presented in Fig. 7 depict that the FE analysis achieved an ultimate load (F_{ult}) of 1257 N at a 0.0021 mm displacement, and the analytical calculation estimates an F_{ult} of 1260 N at a 0.0020 mm displacement. Mutually exhibiting an error less than 4%. Therefore, both the FE simulation and analytical approach effectively capture the interlayer tensile capacity of the 3DCP

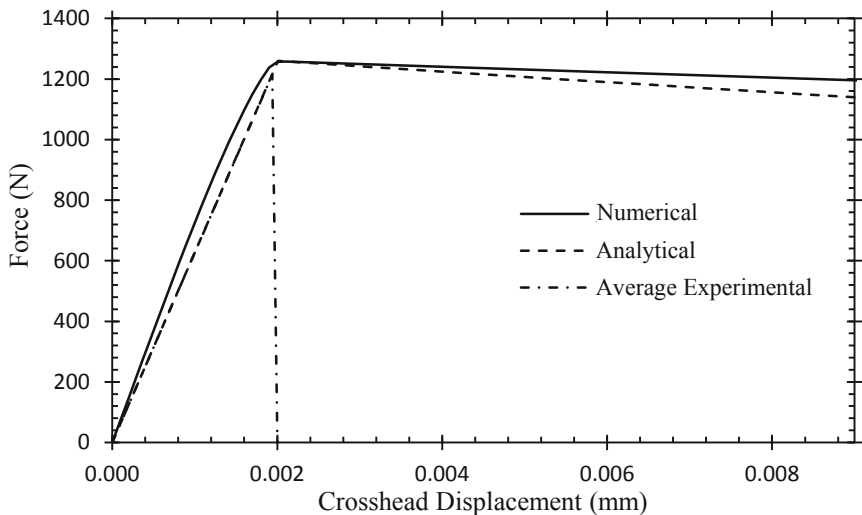


Fig. 7. The average direct tensile test results for the experimental procedure; as well as, the respective analytical, and numerical (FE) simulation results.

specimens at a mesoscale. However, it is recommended that the crack mouth opening displacement (CMOD) experimental procedure be conducted for subsequent experimental endeavors. This will yield a more accurate representation of the ITZ's response to the applied loading, allowing the post-peak behavior to be experimentally captured.

5 Conclusions

In this research, the differential interlayer capacity of 3DCP specimens is mechanically tested in direct tension (DTT), Iosipescu shear (IST), and orthogonal compression. The experimental findings relating to the cohesive characteristics are validated via supplementary mesoscale analytical calibration and FE analysis procedures. The following main conclusions are drawn from this research:

1. The FRPC samples display brittle fracture in both shear and tension when loaded unfavorably over the interlayer transfer zone (ITZ). In both instances, the longitudinal capacity exceeds the ITZ capacity by factor two.
2. The orthotropic compressive capacity is lowest perpendicular to the interlayer, followed by the parallel direction. Mutually exhibiting an approximate 50% reduction when compared to the compressive capacity of the FRPC's matrix, which is attributed to water curing of cast specimens versus air curing of the printed specimens.
3. More robust 3DCP structures are viable if individual sections are orientated such that the ITZ is favorably aligned relative to the ultimate load components.

Cohesive Zone Modeling (CZM) appears a promising numerical modeling technique for validating the tensile ITZ's response of 3DCP elements at a mesoscale. However, refinement of the experimental methods employed is advised for subsequent experimental endeavors. Considering the aforementioned, due diligent consideration is required to account for the fissile nature of 3DCP components. Macroscale structural analysis procedures that effectively capture the composite response of 3DCP structures will be paramount to the scalability of this emerging construction and fabrication process.

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3D Printing of Concrete: The Influence on Chloride Penetration

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Abstract. 3D concrete printing is one type of additive manufacturing (AM) which comprises all modern techniques of fabricating building elements layer by layer. It shows great perspectives with respect to freedom of form, time management and eco-friendly use of the material as the material is only applied where it is necessary. However, due to the lack of formwork and the layered end result, this construction technique induces more shrinkage, internal voids and crack formation, increasing the amount of preferential ingress paths for chemical substances. The additional amount of voids caused by this layered fabrication technique will not only induce anisotropic properties on a structural level, but will also affect the microstructure and durability of the printed specimens. For the aim of this research, 3 different time gaps are selected to investigate the influence of the layered construction process on chloride penetration and a comparison with traditional cast concrete was made. First results showed that the print process affects the chloride penetration in a significant way. Although the ingress front is uniform in both cases, the chloride ingress is approximately three times higher in case of specimens fabricated with a zero minute time gap compared with traditional cast elements and this only after one week of chloride exposure. An increased time gap increases the porosity at the interface and consequently also the chloride ingress rate of the printed elements.

Keywords: 3D printing · Microstructure · Chloride penetration · Durability

1 Introduction

Nowadays, the newly developed 3D print technology becomes increasingly important as it allows the construction industry to deal with a higher shape complexity due to the lack of time consuming formwork. This in combination with a decreased construction time and a more eco-friendly use of the material leads to a technology with a lot of perspectives. Although the manufacturing process shows many advantages, some counteracting aspects on a structural and durable level have to be considered. First of all, the implementation of reinforcement in 3D printed concrete elements is a critical challenge. At this moment, no satisfactory solutions are available yet but they have to

be addressed in order to pave the way for large-scale industrial implementation of 3D printing for structural components [1]. Secondly, due to the lack of formwork, printed elements are immediately exposed to environmental conditions (wind, rain, variable temperatures...) which might cause a rapid loss of water by evaporation. Consequently, focusing on the durability aspects of the material, shrinkage and more specifically drying shrinkage becomes one of the major obstacles as it will lead to unwanted deformations. These deformations are (partly) restrained by the previous layer, and since traditional curing procedures do not fit the new production technique in a proper way, shrinkage stresses and cracking becomes more and more important. Additionally, due to the layered concept of this technique, printed elements show an anisotropic behavior, with a higher porosity and weaker interfaces as a consequence [1]. Both phenomena will affect the transport properties of printed elements and increase the amount of preferential ingress paths for chemical substances (chlorides, CO_2 ,...) significantly.

As mentioned before, the implementation of reinforcement in printed elements will be extremely important. Previous research [2, 3] showed that, in case of reinforced concrete, the ingress of chlorides and the subsequent initiation and propagation of reinforcement corrosion is one of the major causes for durability problems. For that reason, a first evaluation of the durability is made based on the chloride ingress capacity of printed elements. To focus mainly on the effect of the manufacturing process and exclude the influence of the mix composition as much as possible, the same printable material is used during the entire experimental program. Within the scope of this research, 4-layered specimens were printed with the same print velocity, but with varying interlayer time intervals (i.e. 0, 10 and 60 min) between the super positioned layers. The results of the chloride penetration tests are correlated with the microstructural changes induced by the changing time gap. To investigate more in depth the effect of the interlayer, a comparison between printed and molded specimens is made.

2 Materials and Methods

2.1 Materials and Mix Composition

The printable mixtures contained an ordinary Portland Cement (CEM I 52.5 N) in combination with standard sand ($D_{\max} = 2 \text{ mm}$), water ($W/C = 0.35$) and a polycarboxylic ether (PCE) superplasticizer with a molecular weight of approximately 4000 g/mol and 35% solids to increase the flowability. The mix composition can be found in Table 1.

Table 1. Mix composition

Material [-]	Amount [kg/m ³]
CEM I 52.5 N	621
Sand 0/2	1241
Water	227
PCE	0.15% [weight of cement]

2.2 Print Process and Sample Preparation

An in house made apparatus (Fig. 1) was used to simulate an extrusion-based 3D printing process. The developed system is equipped with an elliptical nozzle (28 mm × 18 mm) and is capable of printing layers with a maximum length of 300 mm, at different velocities and different deposition rates. For the purpose of this study, a linear printing speed of 1.7 cm/s and a layer height equal to 10 mm was selected.

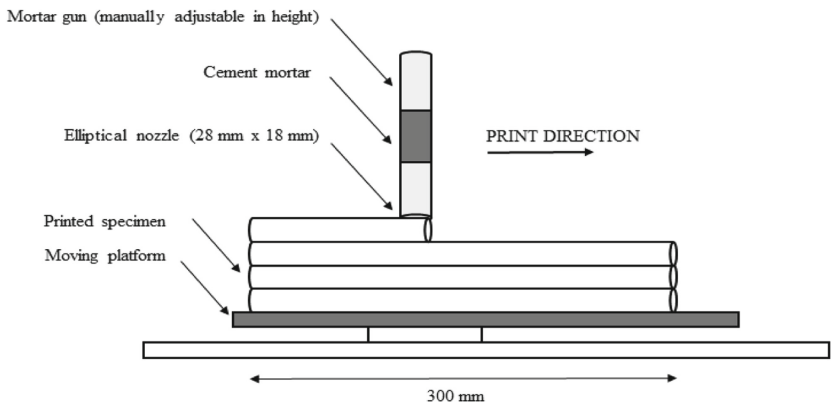


Fig. 1. Schematic illustration of the extrusion based 3D print process

Sample preparation starts by filling the 3D print apparatus with cementitious material and extruding the material through the nozzle with a predefined speed. For each sample, a single base layer was extruded. After a predefined time interval (0, 10 or 60 min), a second layer was deposited on top of the previous one and this process was repeated until four layered specimens were obtained. In case of a zero minute time gap, the four layers were printed from the same batch of material. However, in case of an increased time interval, fresh mortar mixes were used to print the super positioned layers to ensure similar rheological properties for all the different layers. After printing, the specimens were cured in standardized circumstances (20 ± 3 °C; 60% RH) until the day of testing (i.e. 28 days after printing).

The chloride ingress rate of printed samples was compared with traditional cast specimens. For these specimens, prismatic molds ($160 \times 40 \times 40 \text{ mm}^3$) were filled in two steps and compacted by jolting 60 times. These molds were then covered using plastic foil and stored in standardized conditions ($20 \pm 3 \text{ }^\circ\text{C}$; 60% RH). After 24 h, the samples were demolded and stored in the same conditions until the age of 28 days.

2.3 Chloride Ingress

The ingress of chloride ions was measured based on the NT Build 443 by performing a non-steady state diffusion test (Fig. 2). In this test setup, samples were sawn from the original 4-layered specimens or from the traditional cast prisms to obtain $40 \times 40 \times 30 \text{ mm}^3$ and $40 \times 40 \times 40 \text{ mm}^3$ prisms, respectively. Subsequently samples were immersed in a 165 g/L NaCl solution at $20 \text{ }^\circ\text{C}$. To ensure one-dimensional chloride ingress through the front surface (Fig. 3), all other surfaces were covered with a double epoxy (Episol Designtop SF) coating. The samples were placed with their uncoated surface upwards, so chlorides could only penetrate via this non-coated surface. In order to prevent evaporation of the water, resulting in an unwanted increase of the NaCl-concentration, the solutions with the immersed samples were stored in a closed box.

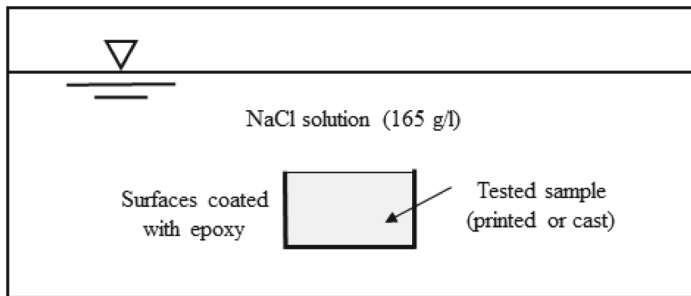


Fig. 2. Schematic representation of the non-steady state diffusion test setup, redrafted after [4]

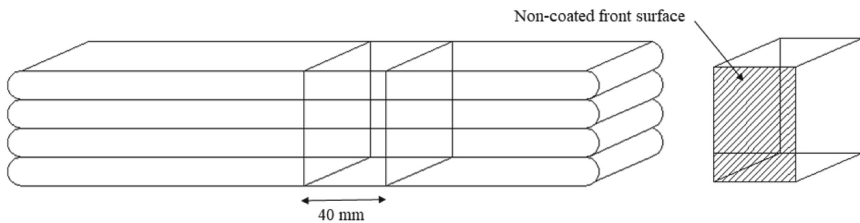


Fig. 3. Schematic representation of a printed specimen, saw-cut from an original printed element, used for measuring the chloride ingress through the front surface

After different exposure times (7, 21 and 35 days), 3 samples were taken out of the solution and split. By spraying an aqueous silver nitrate solution (AgNO_3 , 0.1 mol/L) on the freshly split surface, two well-defined regions could be easily distinguished. The

first region has a whitish color, as the silver ions react with the chloride ions to form silver chloride, a white precipitate. This region visualizes the penetration depth of the free chlorides. The second region colors brown after spraying, and this is formed by silver oxide precipitate generated by immediate decomposition of silver hydroxide. This second region corresponds with the region that is assumed to be free of chlorides. However, this second region is not completely chloride free as the discoloration only happens at a certain chloride concentration. The boundary between the two regions is generally referred to as the discoloration boundary.

After photographing the split surfaces, ImageJ analysis was used to calculate the penetrated area (Fig. 4(a)) and the penetration depth as a function of time for the predefined time intervals. Due to the irregular shape of the printed specimens, the penetration depth is expressed relative to the total width of the specimens (Fig. 4(b)).

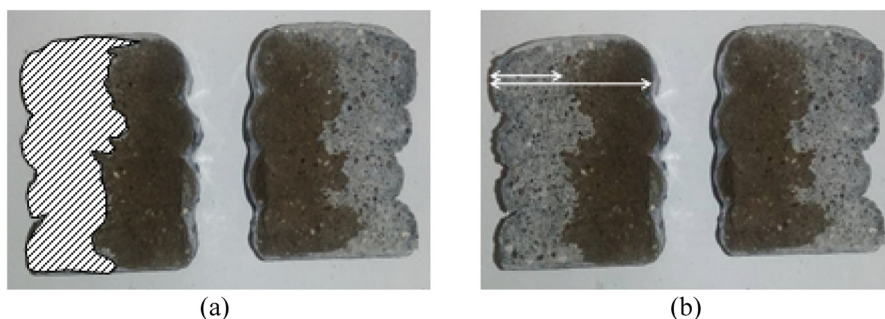


Fig. 4. Chloride penetration area (a) and chloride penetration depth (b)

3 Results and Discussion

Figure 5 represents the chloride penetration rate and the relative chloride penetration area as a function of time in case of traditional cast (REF) and printed specimens with different time gaps (T0, T10 and T60). Based on Fig. 5, one can conclude that compared with molded specimens the chloride ingress is higher in case of printed samples. As the chloride penetration is highly influenced by the porosity of the specimens, this phenomenon can be attributed to the lower amount of voids present in molded specimens, as these are compacted during the fabrication process confirming the assumption that 3DCP introduces a higher amount of pores.

The ingress behavior of the chloride ions in case of specimens printed with a zero minutes time gap is comparable with molded specimens. Statistical analysis of the obtained results reveals that the difference between the chloride ingress measured after one week and five weeks of exposure is not significant and can be classified as similar. Increasing the interlayer time interval increases the chloride ingress of the specimens and these results can be related to previous measurements performed by the authors [5]. First of all, the latter investigations showed that the application of a 60 min time gap

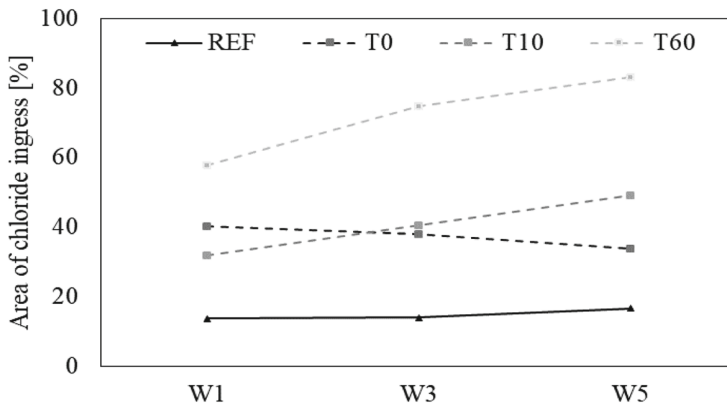


Fig. 5. Chloride penetration rate as a function of time in case of traditional cast (REF) and printed specimens with different time gaps (T0, T10 and T60)

induces a higher amount of pores. Additionally, these layers are exposed to environmental conditions for a longer time and the effect of drying shrinkage becomes more significant resulting in a higher amount of micro cracks. The combination of both phenomena leads to a higher amount of preferential ingress paths for chlorides.

Figure 6 represents the chloride penetration depth relative to the total width of the specimen and expressed as a function of time. In case of molded specimens (Fig. 6(a)), the chloride front is almost vertical over the entire specimen, stating the assumption that the material is homogenous due to the fabrication process. In case of a zero minute time gap (Fig. 6(b)), the same conclusion can be made. A higher porosity increases the penetration ability, but based on statistical analysis, the ingress front can be assumed as vertical over the entire sample height. Consequently, one can conclude that the application of a zero minute time gap results in a, by approximation, homogenous material. The latter correlates with previous investigations, where in case of a zero minute time gap, a uniform water ingress was observed during neutron radiography measurements [6].

In case of a higher interlayer time interval (Fig. 6(c) and 6(d)), even after one week of exposure, the deteriorated interlayer quality becomes more clear and chlorides penetrate deeper into the interlayer. An interlayer time gap of 60 min results in an almost completely penetrated sample.

Based on Fig. 6, one can also conclude that, although statistical analysis showed for a zero minute time gap that the difference in chloride ingress over time is not significant, the chloride ingress front is never as homogenous as in case of molded specimens. This can also be attributed to the difference in exposure conditions (changes in temperature or relative humidity,...) or the difference in porosity between the cement paste and the aggregates (i.e. the inclusion of more air voids during the printing process [7]). Although the researchers tried to keep the environmental circumstances as similar as possible, some process related items cannot be avoided. To obtain a more quantitative analysis of the chloride content, the above mentioned investigations are extended by performing potentiometric titrations on ground powders, but these results are not included in this paper.

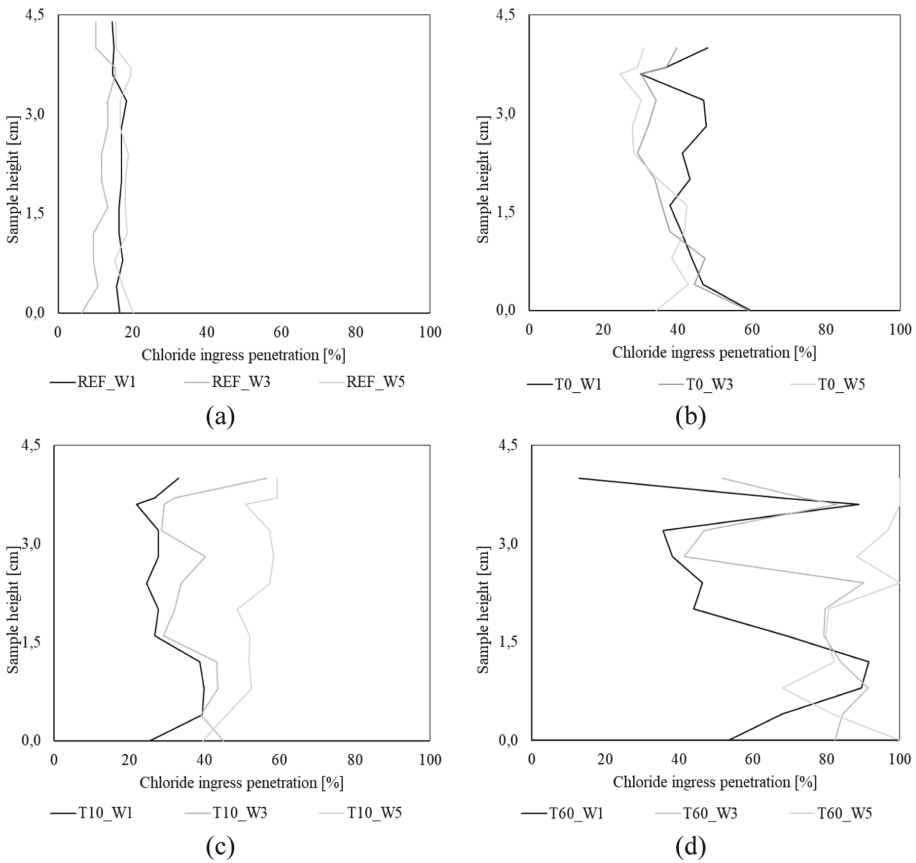


Fig. 6. Chloride penetration depth as a function of time in case of (a) molded specimens and printed elements with a time interval equal to (b) 0 min, (c) 10 min and (d) 60 min

4 Conclusions

Within the scope of this research, the effect of an increased interlayer time interval on the chloride ingress rate was investigated and compared with the chloride ingress in case of traditional cast specimens. The following conclusions could be drawn:

- Compared with molded specimens, the chloride ingress is higher in case of printed specimens. This phenomenon can be attributed to the increased porosity induced by the printing process;
- An increase in interlayer time interval results in an increased amount of penetrated chlorides and a higher ingress rate. The latter can be related to the enlarged exposure to environmental conditions before printing a new layer and consequently the formation of more micro cracks and the inclusion of more pores;

- The ingress front in case of molded specimens is uniform over the entire sample height and the same conclusion can be made for printed specimens fabricated with a zero minute time gap;
- When applying a higher interlayer time interval, the deteriorated quality of the interlayer affects the chloride ingress in a negative way.

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Effect of Heat Curing and E6-Glass Fibre Reinforcement Addition on Powder-Based 3DP Cement Mortar

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Abstract. Powder-based 3D printing is one of the most promising techniques in additive manufacturing. The speed, resolution of the printed part and complicated geometries are important features in this technique and these features are usually not experienced in traditional construction techniques. This study aims to discuss the concept of using a custom-made powder (cement mortar) instead of a commercial (gypsum) powder in 3DP. Therefore, broad investigations are required to study and understand the details of the cement mortar 3D printed scaffold. This paper discovers the effect of heat-curing and addition of E6-glass fibres as reinforcement for the printed specimens. The results show that the mechanical properties of the cement mortar are improved through a heat-curing procedure. Addition of fibre reinforcement enhances powder flowability consistency and surface roughness throughout. Experiments are conducted on printed 50 mm cubic specimens, cured in an oven at different temperatures. The optimum heat-curing temperature is found to be 80 °C to achieve the highest compressive strength in cement mortar specimens. Detailed 3D laser scanning of the printed cement mortar specimens is conducted. The 3D laser scanning results found rougher surface in cement mortar when it is not reinforced with glass fibre.

Keywords: Powder-based 3DP · Cement mortar · Glass fibre · Compressive strength · Surface roughness

1 Introduction

The increasing need for speed, quality and adapted design in the construction industry, pushes the additive manufacturing to another level of applications. The procedures for constructing structural members should be reconsidered and advanced for robust structures in the construction field [1].

Earlier studies have recognized three main techniques for the 3DP powder-bed process [2]: (i) selective cement activation; (ii) binder jetting; and (iii) selective paste intrusion. The selective binder activation process is usually known as powder-bed printing (binder/inkjet printing) [3, 4] and it has been used in many applications for medical and biomedical purposes [5]. The key mechanism of the inkjet technique is to allow a drop of binder (water) to fall through a certain height on the bedded dry powder. The particular binder, that is used, has a major effect on the resolution,

dimensional accuracy and surface finish of the printed parts [6, 7]. The printer that is used in this study is a commercial printer, ProJet CJP 360, developed by Z-corp. However, all types of powder-based 3DP adopt a similar process. This printer has a maximum resolution of (300 × 450) Dots Per Inch (DPI) [8]. The resolution is highly dependant on changes of the powder particle sizes and binder content.

According to Aydın and Baradan [9], alkali activated slag mortar is more suitable to cure in autoclave when it has low Na_2O . Another study investigated the composition of inner C-S-H products and the hydration of the Portland cement mortar [10]. The mortar was cured at 4 h or 28 days pre-cure at 20 °C before heated at 90 °C for approximate 12 h and then stored in water at 20 °C. Their results showed that the C-S-H formed was denser and contained high sulfate at 90 °C than the C-S-H formed at 20 °C. This has motivated significant research efforts on the application of different types of cement (for example, Calcium Aluminate cement and ordinary Portland cement) at different temperatures so as to find the optimum strength and optimum heat resistance of cementitious materials for 3DP. Research is also being conducted into the use of fibre reinforcement to enable the mortar to exhibit improved mechanical properties [11]. There are only a few studies particularly related to fibre reinforced gypsum and cement mortar for 3DP technology. Feng, Meng [12] used Fibre Reinforced Polymer (FRP) sheeting to reinforce the external surface of the printed gypsum prism by bonding it with resin. Christ, Schnabel [13] used chopped glass fibres with a length of 1–2 mm to prepare a gypsum reinforced scaffold which is very short filaments and is not convenient for reinforcement. Farina, Fabbrocino [14] also utilised the 3D printed rebars, made from polymeric and metallic fibres, embedded manually, in the cast-in-place mortar to compare reinforced specimens. Hence, the use of glass fibre as reinforcement in 3D printed components appears to be more feasible than using other types of fibre. In the present study, E6-Glass fibre with a length of 6 mm was used to print mortar specimens in the powder-based 3DP technique.

In addition, former studies on surface roughness and resolution are conducted on cast-in-place mortar prisms with different surface roughnesses 3DP polymer rebars [15]. Their study found that the smooth surface rebar could not be held by the mortar particles, whereas the rebar with a rough surface had improved performance. On the other hand, the surface roughness of the printed cementitious object has been found to be directly related to the powder particle sizes and the powder bed in the build-chamber [16]. Another factor which affects the resolution of the object is the flowability of the powder and the spreading of the powder particles on the build-chamber (build bin) [16, 17]. Overall, there is not enough investigation on the surface roughness of cement mortar powder-based 3DP. In this paper, the surface roughness of glass fibre reinforced and unreinforced 3DP mortars are measured and compared.

The objective of this study is to experimentally examine the performance of 3DP mortar in the powder-based printing technique under heat cured conditions and in the presence/absence of fibres to reinforce the printed specimens. The compressive strengths of the 3DP mortar at various curing temperatures are evaluated until the optimised maximum compressive strength of the printed specimen was found.

2 Materials

2.1 Material Properties

The modified cement powder was formulated based on the commercial powder, ZP 151, whose major chemical composition was calcium sulphate hemihydrate ($\text{CaSO}_4 \cdot 0.5\text{H}_2\text{O}$) (80–90%) produced by the 3DSystems [18]. The particle sizes were produced to be as close as possible to the commercial material. For further detail and relationship between particle sizes refer to earlier studies [3, 4].

The modified mix that was used for powder-based 3DP in this research contained 67.8% of Calcium Aluminate Cement (CAC) using a ranging sieve of 75–150 μm , 32.2% of Ordinary Portland Cement (OPC) and 5% of fine sand as a percentage of total weight. The selection of materials was based on the particle size flowability and quick setting properties of the materials. For example, CAC had good resistance for abrasion, acid resistance and quick setting. In the 1950s, the CAC mortar was used as lining for the Portland concrete pipes in Kuala Lumpur. It has also been used in many other countries such as Egypt and South Africa [19].

The physical properties of the E6-glass fibres used in printing fabrication are shown in Table 1.

Table 1. Physical properties of chopped E6-glass fibre filament

Fibre type	Length (mm)	Filament diameter (μm)	Specific gravity (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Expansion coefficient (10^{-6}K^{-1})
E6-Glass fibre (Trojan)	6 ± 1	13 ± 1	2.62–2.63	2500–2700	81	6

2.2 Powder Mixing

After selecting the type of materials and their mix proportions, the materials were blended homogeneously. The modified powder was thoroughly mixed using a Hobart mixer at a speed of 1450 rpm.

The homogeneity and consistency of the powder were significant factors that must be controlled when in pursuit of superior surface roughness and strength results. Hence, the speed of the mixer and the blending time were found to be the main contributors to the homogeneity of the powder and for production efficiency of 3DP objects [20].

3 Methods

3.1 Specimen Preparation

Specimens with dimensions of $50 \times 50 \times 50$ mm were tested for compressive strength. As shown in Table 2, three specimens for each group were prepared for each test, based on 6 different curing conditions.

Table 2. Detailed number and dimension of specimens

Specimen description	CAD dimensions (mm)	Number of specimens	Printed plane
Plain cube	50 × 50 × 50	18	XY
Fibre-reinforced cube	50 × 50 × 50	18	XY

Figure 1 provides all details of the planes (XY, XZ, YZ) and the applied loads on the XY plane. Figure 1 also displays the green part for a 3DP mortar cube (the green part is defined as the fabricated part after printing and removal from the build-chamber of the printer, prior to commencing any post-processing procedure such as curing).

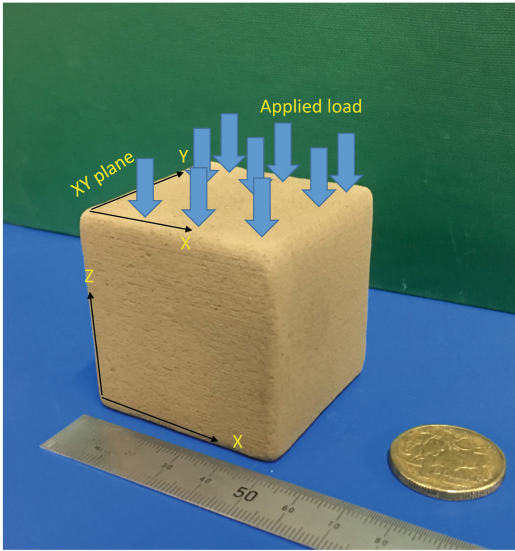


Fig. 1. The green part of the 3DP cement mortar cube 50 × 50 × 50 mm and illustration of a cube tested on the plane (XY)

3.2 Post-processing of Specimen

After a specimen was printed, it was left in the printer for approximately 2 h before curing. The post-processing consists of (a) curing one group of specimens for 28-days in tap water; (b) curing another group of specimens in the oven for 3-h, storing in water for 28 days and then drying in the oven for 3-h. This same basic post-processing sequence was used for all specimens, but at various temperatures. Specimens were cured under the following different conditions: cured in tap water only, (cured for 3-h at 40 °C, 28-days water, 3-h at 40 °C), (cured for 3-h at 60 °C, 28-days water, 3-h at 60 °C), (cured for 3-h at 80 °C, 28-days water, 3-h at 80 °C), (cured 3-h at 90 °C, 28-days water, 3-h at 90 °C) and (cured for 3-h at 100 °C, 28-days water, 3-h at 100 °C).

3.3 Compressive Strength Test

Cubic specimens were subjected to the compressive strength test. The compressive strength test was performed for the 3DP specimens according to the ASTM standard [21]. A total of 36 specimens were printed and tested, including 3 specimens for each curing process and 3 specimens with the presence/absence of glass fibre. The rate of loading in the compressive strength test was fixed at 0.833 kN/s.

4 Results and Discussion

4.1 Compressive Strength

Influence of the strength of material is significant to measure the ability of materials behaviour to resist the applied load.

Figure 2 presents the compression strength of the printed mortar using 1% E6-glass fibre as reinforcement and curing at different temperatures. Specimens curing at 80 °C attained the optimum compressive strength for the printed mortar. The compressive strength of mortar with 1% glass fibre was recorded as 37.88 MPa, which is quite suitable for the construction industry and precast construction applications.

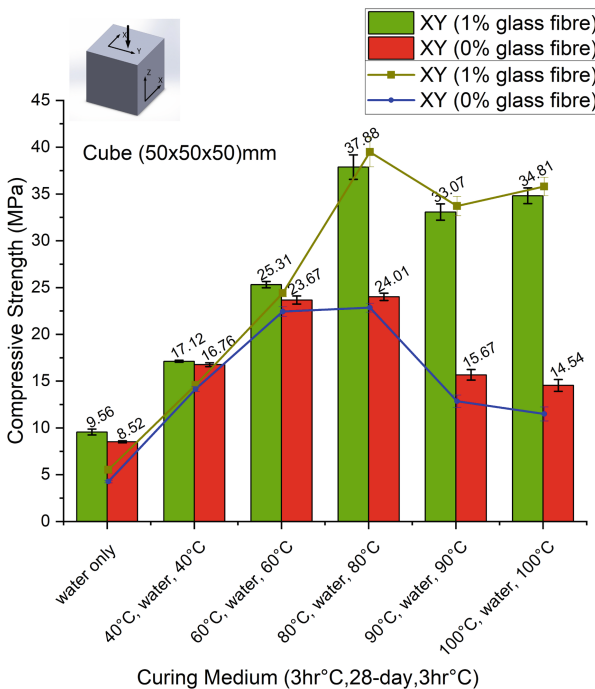


Fig. 2. Compressive strength of mortar specimen 50 × 50 × 50 mm with/without glass fibre using different curing media

The increased strength in the cement mortar proportional to the increase in temperatures was due to the greater reaction level of the cement mortar at the raised temperatures at early ages. Curing in an oven accelerated the reaction of the cementitious process. Fast hydration and a high early compressive strength were observed as the temperature was increased [22].

These results are positive for the construction industry and precast construction applications. This study used optimal saturation levels that are detailed in the earlier studies [3, 4] to show the strongest plane and direction in addition to the optimised elevated temperature, which is the optimum to attain the highest compressive strength. For long term durability and checking the quality of the materials, it is necessary to conduct further investigations, such as monitoring the surface quality of the printed structure in harsh environments and checking the serviceability limit state of the printed structural members.

4.2 Surface Roughness

Abbreviation “Ra” is a value used to describe the surface textures of the materials. Ra expresses as arithmetic mean deviation of the roughness profile which is determined by height deviation of the surface from a mean line within the evaluation length. A substantial change has been observed when glass fibre was added to the cement mortar.

Adding fibres into printed specimens significantly affect the porosity and surface roughness. The porosity of the composite materials has an impact on the mechanical properties of the specimens. The porosity of the printed scaffold reduced by fibre reinforcement due to the well-distributed fibres on the powder-bed chamber before the printing process. Figure 3 shows the surface roughness profile of printed specimens in the presence and absence of glass fibre. That figure clearly shows a reduction in the roughness of the surface morphology of the cubic specimen. Overall, the surface roughness of the cubic cement mortar specimen with 1% glass fibre is $18.57 \pm 1.35 \mu\text{m}$ and that of the specimen without glass fibre is $22.31 \pm 3.72 \mu\text{m}$.

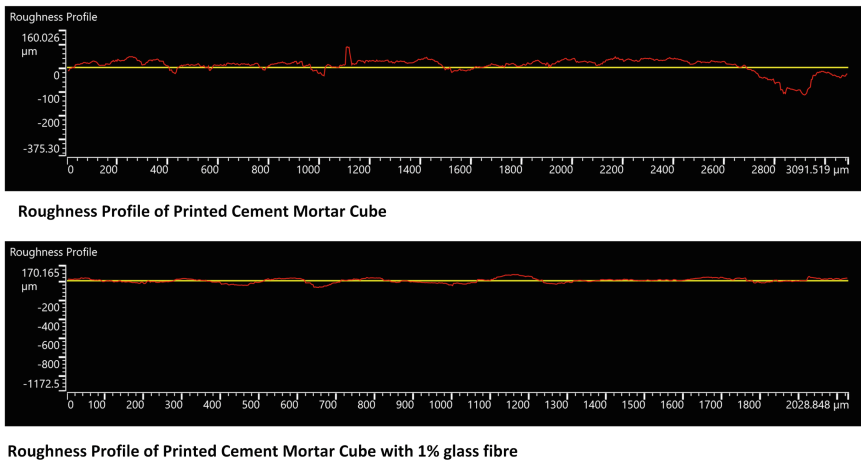


Fig. 3. Comparison of printed cement mortar specimens in the presence/absence of glass fibre

Figure 4 shows the 3D laser scanner capture of the fibre filaments in the printed specimens. It clearly shows the approximate length at the edge of the specimen and the diameter of the specimen. The approximate length of the filaments extending beyond the edge is approximately 400 μm , with the rest of fibre's length inside the printed mortar. The diameter is approximately 13.49 μm . Consequently, this is proof that the filament is not damaged during printing and solidifying.

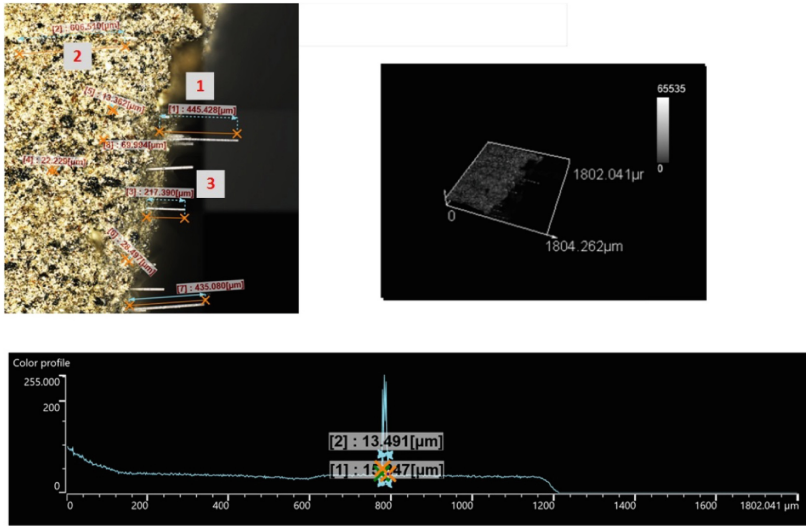


Fig. 4. Filament diameter and length of the fibre in the printed specimens. In the top left image (1) fibre filament extends 445 μm beyond the edge of the specimen; (2) fibre filament length of 606 μm in the specimen, (3) fibre filament length of 217 μm beyond the edge of the specimen.

5 Conclusions

From this study the following conclusions can be achieved:

- 3DP technology is emerging as an advanced technique to construct highly detailed complicated geometries, which are conventionally difficult to construct
- The maximum compressive strength was recorded at 80 °C in the presence/absence of 1% E6-glass fibres
- The surface roughness measurements showed that cement mortar specimen with fibre had an even and uniform surface compared to specimens without fibres

Further research on powder-based 3DP is required, specifically on post-processing, curing, and infiltration, early age shrinkage of the printed specimens such as autogenous shrinkage, chemical shrinkage and plastic shrinkage. Ideally, that research should focus on broader applications for construction purposes, such as an investigation of larger-scale 3DP in real-life.

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Effect of Polypropylene Fibres on the Mechanical Properties of Extrudable Cementitious Material

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Abstract. 3D Concrete Printing (3DCP) has aa potentiality to produce complex, geometries and can modify the details rapidly using a printer integrated with a pump and nozzle. From the earlier studies on 3DCP, it is distinguished that the rheological behaviour of the material, printing direction, and printing time may have significant effects on the overall structural behaviour of the printed structure. The layered concrete may create weak joints in the specimens and reduce the load bearing capacity in terms of compressive, tensile and flexural strength that requires stress transfer across or along these joints The present study focuses on the examination of the effect of adding polypropylene (PP) fibres on the failure behaviour of print mortar on printed concrete, on different print directions. The Silica Fume (SF) based control mix was used in the analysis with fibre addition in different mass fraction of binder ranging from 0.5% to 3.0%. Those mixes were designated after the detailed fresh property analysis and control cementitious specimens without fibre inclusion were also printed for comparison. The specimens were collected in different orientations from manual extruded concrete blocks and tested for mechanical properties. For the materials tested, it is found that the mechanical properties such as compressive and flexural strength of extruded samples are governed by its printing directions. The mixes with 1.0% and 0.5% PP fibre addition exhibit the better performance in terms of flexural strength and 0.5% PP mix can be considered as the optimum fibre content with respect to the compressive strength.

Keywords: 3D concrete printing · Additive manufacturing · Polypropylene (PP) fibres · Mechanical properties · Compressive strength · Flexural strength

1 Introduction

3D concrete printing or Additive manufacturing technology is one of the rapidly developing areas, as illustrated by the high frequency in which new projects are being presented by a growing number of enterprises and research institutes worldwide [1]. This technology is transforming the construction industry drastically, making it cheaper and more efficient. It is a great step towards sustainable development, which can provide safe and affordable shelter for those in need. The technology of producing houses and other

structures using this method has dramatically improved since 2010 [2]. However, in terms of the integrity and durability of the structure, there is more to discover.

Extrusion-based printing is an emerging type of 3DCP, which has been envisioned for on-site construction and to build the desired structure layer by layer without using any kind of formwork [3]. The prime concern of this method is to define the suitable concrete material which meets the structural and thermal performance requirements of the structure [4]. Malaeb *et al.* [5] proposed the selection criteria of an optimum mixture for 3DCP as follows. The compressive strength has to be optimized while maximizing the workability and the material has to achieve the required flow in the system yet maximize buildability upon pouring. In addition the concrete setting time has to be minimized while maintain the suitable setting rate to ensure the bonding with the subsequent layer.

Moreover, Kazemian *et al.* [6] has identified the layered structures are likely to be anisotropic as voids can form between layers to weaken the structural capacity. Similarly, Paul *et al.* [7] studied, the mixed isotropic and anisotropic properties of printed concrete structures in different direction distinct to the cast specimens, as one of the key drawbacks of this practice. Therefore, a high strength in compression, flexural, tensile bond will also be the main objectives in developing this printable concrete. Paul *et al.* [7] and Sanjayan *et al.* [8] investigated the influence of testing direction in the mechanical properties of 3D printed concrete and produced relatively acceptable results. Both increasing and decreasing tendency in the mechanical strength was found in the printed specimen depend on the testing direction, when compared to the strength of cast specimen. Furthermore Nerella *et al.* [9] investigated the bond quality between printed layers through applied forces in both parallel and perpendicular directions to the layer interface plane.

The incorporation of conventional steel reinforcement into the layering process is another major constraint of extrusion-based 3DCP technique [10, 11]. Moreover, these freeform components which are built without formwork might result in crack propagation [6]. Hence, a low shrinkage also should be achieved with the end product. As an alternative solution, researchers recommended the inclusion of short fibre reinforcements partly or completely into the material. However, it should be noted that the anisotropic behaviour would be more pronounced for the mixtures with fibre compared to the mixtures without fibre [10].

Limited studies have been conducted on the effect of fibre incorporation in extrusion-based 3DCP. Recently, Nematollahi *et al.* [10] investigated the effect of polypropylene (PP) fibres on the fresh and hardened properties of 3D printed geopolymer mortars and Nematollahi *et al.* [11] also conducted the studies on the effect of type of fibre on inter-layer bond and flexural strengths of extrusion-based 3D printed geopolymer. Panda *et al.* [12] examined the effect of incorporation of chopped glass fibres with different lengths and volume fractions on the hardened properties of 3D printed geopolymer. Nematollahi *et al.* [10] and Panda *et al.* [12] identified a negligible increase of compressive strength and considerable increment in the flexural and tensile strengths due to the fibre addition. But in contrast, Hambach and Volkmer [13] achieved high flexural and compressive strength by adding short different types of fibres into 3D printed mixture of OPC paste. Effective fibre alignment was reported as the key factor which directed to a remarkable increase of flexural strength of these

mixtures. Furthermore, Bos *et al.* [14] studied the effect of adding short straight steel fibres on the failure behaviour of print mortar through several tests on cast and printed concrete, on different scales. However, a detailed analysis on the effect of fibres in the mechanical properties in different directions has not been investigated and these studies have indicated that further analysis have to be performed for different mix designs to explain the fluctuating strength behaviour.

Therefore, the present study is emphasized on the impact of polypropylene (PP) fibres on the mechanical properties of a novel extrudable concrete mixture. The main aim of this paper is to investigate the mechanical properties such as, compressive and flexural strength of extrudable concrete related to the printing direction with different fibre content.

2 Experimental Investigation

In the current experimental study, a novel Silica Fume (SF) based cementitious material mix was used to produce the test specimens in layers. Six mix designs with different polypropylene (PP) fibre content were studied for compression and flexural strength. Optimal fibre content to have the better strengths has been proposed.

2.1 Materials and Mix Proportions

Resources available in the UK were employed as source materials for this study. Type-I Ordinary Portland Cement (OPC) and tap water were used for all the mixtures. Midas sand and Limestone fines were used as fine aggregates. Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) were used as a partial cement substitute. A high Range Water Reducing Admixture (HRWRA) was added with water in order to reduce the water consumption while improving the workability and strength. In addition, to adjust the viscosity of the mixes to achieve the extrudability and buildability standards, a Viscosity Modifying Admixture (VMA) was also used. 12 mm length Polypropylene (PP) fibres were used with different volume percentages to print fibre-reinforced cementitious mortars. These fibres serve as shrinkage reinforcement for a printing mixture.

Before the initiation of the experimental tests, numerous trial runs were conducted on different mix compositions to calibrate the extrudable mix. Finally, the extrudable mix was chosen to examine the fresh concrete and its mechanical behaviour relative to the printing direction. The analysis results of fresh concrete property the study of the authors [15] on extrudable SF based mortar were used to determine the preliminary proportions. Fibre was added in different volume fraction of binder in 0.5, 1.0, 1.5, 2.0 and 3.0%. Control cementitious specimens without fibres were also printed for the comparative study. The material composition investigated in this study are given in Table 1. All proportions were kept constant in the control mixes, except the fibre and the amount of water. According to the authors' previous study [15], the water/binder ratio was maintained in a range of 0.31–0.33. The fibres and water content variation is given in Table 2.

Table 1. Material composition of the control mix (kg/m³)

Binder	Cement	350
	GGBS	185
	SF	100
Fine aggregate	Midas sand	500
	Limestone fines	250
Admixtures	HRWRA	8
	VMA	4
	Block	10

Table 2. Fibre and water content variation (kg/m³)

Mix ID	Water	W/B	Fibre
Control mix	195	0.31	0
PP 0.5%	195	0.31	3.18
PP 1.0%	200	0.31	6.35
PP 1.5%	210	0.33	9.53
PP 2.0%	210	0.33	12.70
PP 3.0%	212	0.33	19.05

2.2 Specimen Preparation

The mixing was carried out in a free fall type mixer with tilting drum and two rotating blades. The mixture was prepared by mixing the binders in designated proportions followed by Midas sand and limestone fines addition. Then, fibres were added to the dry mixture. A sufficient amount of water was added to avoid the loss of material while mixing and then the remaining water was added homogenously with admixtures. The total mixing time was maintained about 7–10 min for all the mixes.

A custom made small scale mortar pointing gun was used to simulate the extrusion-based 3DCP process. A 3D printed nozzle with rectangular opening of 25 mm × 25 mm was attached to the end a metallic cylinder as shown in Fig. 1. The samples were produced as blocks with approximate size of 300 mm (L), 200 mm (W) and 50 mm (H) with single layer measurements are 220 mm (L), 25 mm (W) and 25 mm (H) and two layers were extruded in vertical direction. The block size was decided as above in order to extract minimum 6 prism samples with standard dimensions for flexural tests from each mixture. The sample preparation is shown in Fig. 2. The second layer was printed on top of the first layer with a time interval of 15 min. The blocks were stowed in a water tank with temperature 19 ± 2 °C for curing and the prism specimens were extracted on the same day of testing. The same procedure was followed to all mixtures.

**Fig. 1.** Extruder**Fig. 2.** Sample preparation

2.3 Mechanical Properties of Concrete

The prism specimens with the dimensions of $160 \times 40 \times 40$ mm were extracted from the printed block for the flexural strength tests. Later, the undamaged ends of the tested prism samples were cut into 40 mm cube specimens for the compression strength tests. The surfaces of the test specimens were also ground to mitigate the influence of surface quality. The resulting variations in the sizes were measured and considered while calculating the final strength values.

Flexural Strength

Flexural strength test was carried out using an Instron testing machine in accordance with BS EN 196-1:2016. All prism specimen were tested on 7, 14 and 28 days under 3 point bending. The loading rate of 1 mm/min with span 120 mm was maintained for every tests. Samples were tested in two directions such as vertical to print direction ($D1_F$) and the direction perpendicular to the layers ($D2_F$). A total of six prism samples as per three for each direction, were tested per test age and the mean strengths were recorded. The loading arrangement is illustrated in Fig. 3 for the flexural tests and Fig. 4 shows the specimens prepared for the flexural test.

Compressive Strength

Cubic specimens of 40 mm were tested to compute the compression strength in accordance with BS EN 196-1:2016. Compression samples were also tested for 7, 14, and 28 days with a loading rate of 2.4 kN/s. The samples were tested in three different directions which are vertical to print direction ($D1_C$) and the direction perpendicular to the layers ($D2_C$) and a direction parallel to the layers ($D3_C$). Three specimen for each direction giving a total of nine specimens were tested per test age and their mean strengths were calculated. The loading arrangement is illustrated in Fig. 5 for the compression tests. Figure 6 shows the specimens prepared for the compression test.

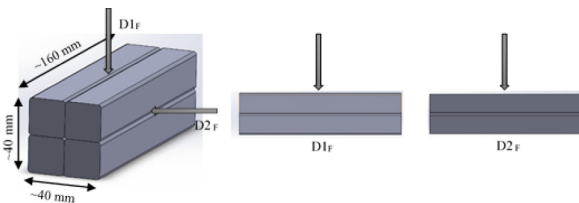


Fig. 3. Loading configuration for flexural tests



Fig. 4. Flexural test samples

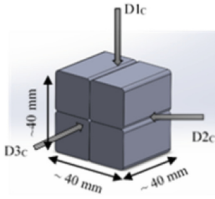


Fig. 5. Loading configuration for compression tests



Fig. 6. Compression test samples

2.4 Results and Discussion

Flexural Strength

Figure 7 demonstrates the flexural strength development of the printed specimens in the vertical ($D1_F$) to print direction within 7, 14 and 28 days. On average, 82% and 94% of 28 days strength is perceived in 7 and 14 days respectively. Similarly, Fig. 8 describe the flexural strength development in the direction perpendicular to the layers ($D2_F$). On average, 85% and 92% strength gain is identified for 7 and 14 days correspondingly. The higher binder/fine aggregate ratio and the lower water/binder ratio are the essential causes for this rapid strength gain.

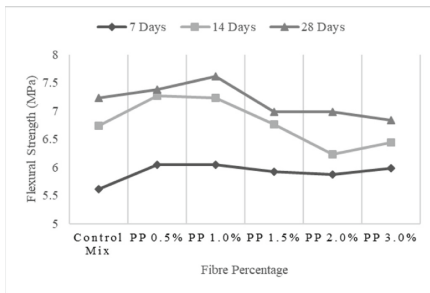


Fig. 7. Flexural strength development over time in $D1_F$ direction

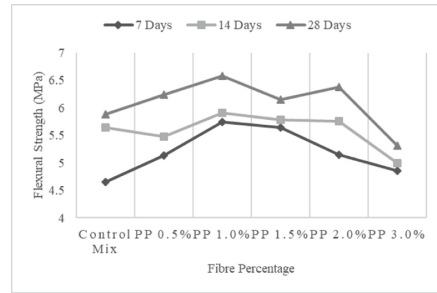


Fig. 8. Flexural strength development over time in $D2_F$ direction

Figure 9 presents the average flexural strength of the printed concrete for two different testing directions on 28 days. The capacities of the specimens tested in $D1_F$ direction is higher than that of the specimens tested in $D2_F$ direction and this pattern is true regardless of the fibre percentage. The mean flexural strength in $D1_F$ direction was 9%–28% higher than that of $D2_F$ direction depending on the fibre percentage. The reasons for this phenomenon could be explained as follows. The bottom layer was

achieved higher load carrying capacity as it was compacted by the following layer. Also, the load was applied to the mid-span of the bottom layer where the maximum tensile stress takes place. Hence, higher capacity is achieved in the $D1_F$ direction compared to $D2_F$.

Comparison between the mixtures with fibres and the control mix without fibre showed that PP fibre reinforcement has a less significant effect on the flexural strength in the $D1_F$ direction. The mix with 1.0% volume fraction of fibre inclusion exhibited 5.4% increase in the flexural strength (7.62 MPa) compared to the control mix (7.23 MPa). Also, 0.5% PP increased the strength by 2.07%. Similarly, for the specimens tested in $D2_F$ direction 11.9% (6.58 MPa) and 6.12% strength increment was achieved compared to the control mix (5.88 MPa) for 1.0% and 0.5% PP respectively. But, a fluctuating behaviour with increasing fibre content was identified. However, the flexural strength is decreased with the increase of fibre content in both direction. The higher fibre addition leads to voids formation inside the mixture and consequently to a reduction in capacity.

Therefore, the mixes with 1.0% and 0.5% PP fibre addition exhibit the better performance in terms of flexural strength.

Compressive Strength

The compressive strength development of the printed specimens in the vertical to print direction ($D1_C$) within 7, 14 and 28 days is shown in Fig. 10. The average strength gain on 7 and 14 days was measured as 78% and 89% of the strength recorded on the 28th day. Similarly, the compression strength development in the direction perpendicular to the layers ($D2_C$) is given in Fig. 11. On average, 77% and 88% strength gain is identified for 7 and 14 days respectively. Likewise, Fig. 12 shows the strength development in the direction parallel to the layers ($D3_C$). On average, 79% and 91% strength gain is identified for 7 and 14 days correspondingly. The strength gain indicates a similar incremental fraction with time in all three direction and also in line with the flexural strength growth.

Figure 13 illustrates the mean compressive strength of the printed concrete for all three different testing directions on 28 days. It is evident that the mean compressive strength of the specimens tested in direction $D2_C$ was relatively lower than that of the specimens tested in the directions $D1_C$ and $D3_C$. This result is true irrespective of the fibre percentage. The adjacent layers of the blocks were printed continuously started from the first layer. Therefore, the bonding between the layers in the adjacent direction has to be investigated further to analyse the strength reduction in $D2_C$ direction. Also, this direction has a lower pressure during the setting process.

The $D3_C$ direction is having mean strengths in between $D1_C$ and $D2_C$ for the control mix and mix with fibre addition of 0.5%. Besides, the mix PP 1.0% shows an approximately identical value of strength on both $D1_C$ and $D3_C$. This is due to the high pressure applied to the material in this direction during the extrusion process. But, the strengths in $D3_C$ direction are surpassing the strengths in $D1_C$ for the mixes with fibres more than 1.5%. The pressure in this direction during the setting process of the

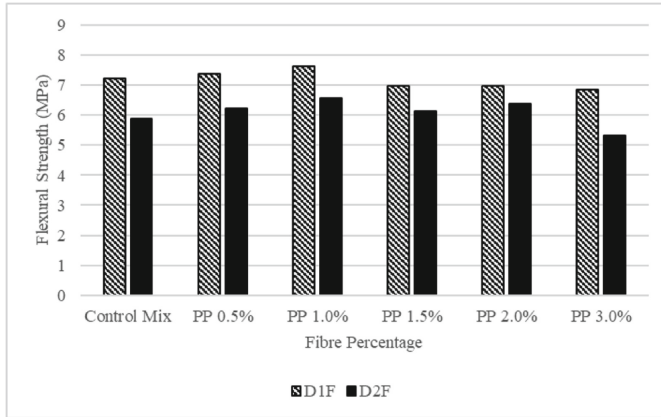


Fig. 9. Flexural strength in 28 days

concrete is the main reason for this pattern. Hence, the average compressive capacity is higher in the D1_C direction when the mixes only have lower fibre percentages. Moreover, the higher fibre content mixes reached the strengths, which is considerably less than that of the control mix.

Comparison between the mixtures with fibres and the control mix indicated that PP fibre addition has a notable influence on the compressive strength in loading direction. The mix with 0.5% volume fraction of fibre inclusion exhibited 27% increase in the strength (67.24 MPa) compared to the control mix (52.79 MPa) and 1.0% PP addition increased the strength by 12.27% in D1_C direction. Also, for the specimens tested in D3_C direction 32.5% (62.63 MPa) and 23.74% strength increment was achieved compared to the control mix (47.27 MPa) for 0.5% and 1.0% PP respectively. A gradual reduction in strength is observable for mixes having fibres more than 0.5% and all the mixes with fibres showed improved strengths compared to the control mix. The specimens tested in D2_C only provided 6.05% increased strength for 0.5% (38.93 MPa) fibre inclusion and 0.3% reduction for 1.0% associated to the control mix (36.71 MPa). However, the compressive strength has also shown a decreasing tendency with the increasing fibre content. This is due to the higher porosity of the mixture followed by the increase in the entrapped air.

Thus, the mixture with 0.5% fibre possessed the maximum compressive strength in all three direction and can be considered as the optimum fibre content with respect to the compressive strength.

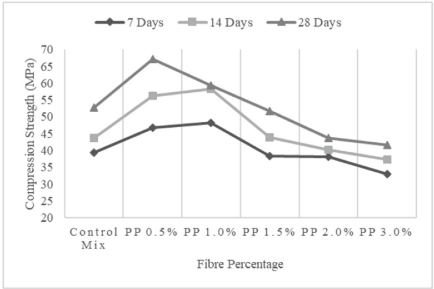


Fig. 10. Compression strength development over time in D1_C direction

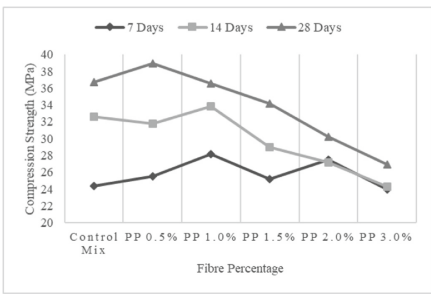


Fig. 11. Compression strength development over time in D2_C direction

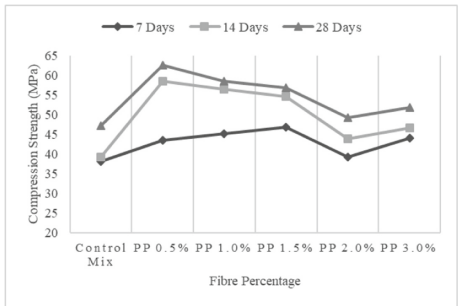


Fig. 12. Compression strength development over time in D3_C direction

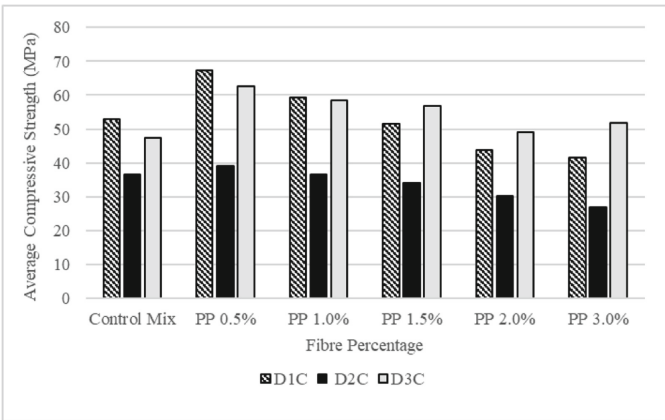


Fig. 13. Compressive strength in 28 days

3 Conclusion and Future Scope

This research work has presented the significant mechanical parameters for consideration in 3D printable construction materials. A novel concrete that has extrudability and buildability which was developed for the custom made extruder was used for this study. Two-layer printed samples were subjected to compressive and flexural testing in different loading directions to determine the hardened properties of the samples. From the results shown in this study, the following conclusions can be drawn:

1. The printing direction affects the mechanical properties of extruded specimens. Depending on the testing direction, both increasing and decreasing trends in mechanical strength can be found in the printed specimens. Moreover, the extrusion process introduced relatively higher anisotropic behaviour in terms of the compressive strength compared to the flexural strength of the printed concrete. The fluctuating behaviour of flexural and compressive strength intends to be investigated more comprehensively in future research.
2. A prominent correlation between the porosity produced by the fibre inclusion and the mechanical properties is inveterate.
3. Mixes PP 1.0% and PP 0.5% designate better performance in terms of flexural strength and PP 0.5% shows enhanced compressive strengths. Furthermore, a detailed research has to be conducted for the fibre inclusion in the range of 0.5% and 1.0% in order to select an optimal mixture.
4. The strength deviation with different amounts of fibre addition with fibre alignment during the extrusion process has to be investigated.

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Improving the Bonding Adhesion of the Cold Joints of Normal and Lightweight 3D Printing Mortars

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Abstract. Two types of mortars were developed for 3D Construction Printing (3DCP), which are normal and lightweight 3D mortars (termed as LATICRETE® 3D Printing Mortar NW and LATICRETE® 3D Printing Mortar LW, respectively). This paper presents the properties of the aforementioned mortars in fresh and hardened states, as well as states of curing for cold joint testing. The fresh properties assessed consist of the determination of flow, viscosity, initial set time, and unit weight. In its hardened state, each type of mortar was tested for its mechanical (i.e., compressive and tensile strengths) and freeze-thaw (i.e., ASTM C666) properties. The printability of the mortars was demonstrated by printing small (20-layer; 12 cm high with 6 mm layer thickness; within 5 min) and large-scale structures (a full-scale villa – normal 3D mortar only). Furthermore, a lab-scale test was developed to assess the bonding strength between layers (both cold and fresh joints). The results of the test indicate that the interlayer adhesion at the cold joint can be improved by applying a bonding agent (i.e., LATICRETE® 254 Platinum) on its surface prior to the print.

Keywords: 3D printing · Compressive strength · Cold joint · Adhesion · Lightweight

1 Introduction

Innovation in construction has been leaning towards the development of advanced materials and new construction methods, which both aim to create a more durable, sustainable and efficient construction process. One of the areas that has been gaining popularity in the past decade is automation in the construction process [1]. Automation in construction involves the use of robotic systems to partially, or fully, build components of structures. One of the rapidly growing automation methods in building construction is additive manufacturing (AM), also known as 3D construction printing

(3DCP), in which a robotic 3D printer is used to build the structure. This method is adapted from conventional AM, in which a designed object is shaped by depositing the material (i.e., polylactic acid (PLA), thermoplastic polyurethane (TPU), acrylonitrile butadiene styrene (ABS)) layer-by-layer. Instead of using the aforementioned materials (i.e., PLA, TPU, ABS), 3DCP typically extrudes cementitious materials. As it is intended for construction purposes, the scale of 3DCP is usually in the realm of tens to thousands of cubic-meters. In 3DCP, the structure is typically designed by using a 3D software. In 3DCP, the material (usually in the form of slurry) is pumped through the hose, extruded at the tip of the printer's head, and deposited layer-by-layer to form the 3D object. The potential benefit of 3DCP over the conventional method includes lowering the overall costs, shortening the construction time, and creating a safer work environment. The cost-cut potential of 3DCP comes from the elimination of the need for formwork [2–5], less manpower [6], lower amount of waste [4, 5, 7], and faster construction time [4, 5, 8]. The ability of the 3D printer, which has multiple degrees of freedom (i.e., 3–7 degrees of freedom), also simplifies the process for constructing complex-shape structures [2, 9] whereas conventional building methods often requires special-fabricated formwork [10]. 3DCP also creates a safer construction process as it requires fewer workers, and most of the work that is done, is done so through automation [5].

This paper presents the properties of two types of 3D printing mortars, termed as LATICRETE® 3D Printing Mortar NW (normal weight) and LATICRETE® 3D Printing Mortar LW (lightweight). The capacity of these mortars to be used in 3DCP was demonstrated in the lab through printing small-scale structures. In addition to the lab work, the capability of LATICRETE® 3D Printing Mortar NW demonstrated printability in the construction of a 3D printed house.

2 Test Matrix, Results and Discussion

2.1 Fresh Properties

The wet density, viscosity, and the flow of the freshly mixed mortars are evaluated in this study. To assess the fresh properties of the 3D mortar slurry, powder of LATICRETE® 3D Printing Mortar NW and LATICRETE® 3D Printing Mortar LW were mixed with water at the ratio of 16% and 45% (weight base), respectively, as the mixtures yielded the same w/cm and were proven to be printable at these levels of water. The wet density of the freshly mixed 3D mortar is measured by filling a density cup with the mortar. The wet density is defined by the weight of the mortar that has fully filled the density cup divided by the volume of the cup (i.e., 100 ml) [1]. The viscosity of the slurries were measured by using Brookfield viscometer with spindle #14 at 10 rpm [1]. The viscosity measurement was ran for 2 min with a reading taken every 15 s [1]. The average of the readings gives the final viscosity value. The flow of the fresh mixture was measured following the ASTM C1437 – Standard Test Method for Flow of Hydraulic Cement Mortar [11].

In addition to aforementioned fresh properties, the initial set time of the mixture was measured following ASTM C266 - Standard Test Method for Time of Setting of

Hydraulic-Cement Paste by Gillmore Needles [12]. The results of flow, density, viscosity and initial set time of LATICRETE® 3D Printing Mortar NW and LATICRETE® 3D Printing Mortar LW mortar are presented in Table 1.

Table 1. Fresh properties of 3D printable mortars.

	LATICRETE® 3D Printing Mortar NW	LATICRETE® 3D Printing Mortar LW
Wet density, g/cc	1.89	1.29
Flow, %	59	100
Viscosity, cP	31250	22500
Initial set time, minute	110	183

The lightweight 3D mortar (i.e., LATICRETE® 3D Printing Mortar LW), as its design, is 32% lighter than its normal weight compatriot (i.e., LATICRETE® 3D Printing Mortar NW). At the printable state, the normal weight 3D mortar is more viscous than the lightweight version as indicated by the viscosity (31250 vs 22500 cP) and the flow measured values (59% vs. 100%). The printability of these two mixtures are demonstrated by printing lab-scale structures as presented in the next section.

2.2 Mechanical and Durability Properties

For the hardened properties, 50 mm (2 in.) cube specimens were cast and tested in compression. The compressive strength test was conducted following ASTM C109 [13] test method by using an Instron 5984. The loading rate was set at 900–1800 N/s (200–400 lbs/s). The compressive strength test results are shown in Fig. 1 with each data point is an average of 2–3 specimens.

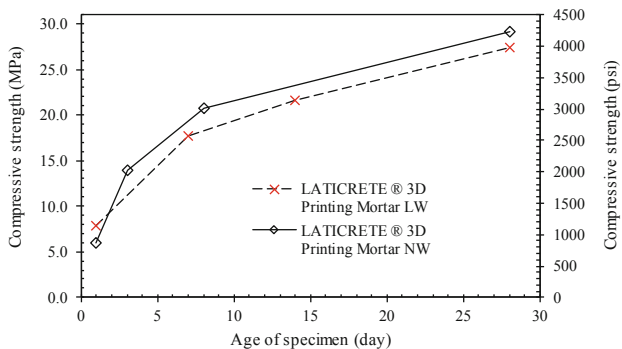


Fig. 1. The compressive strength of normal weight (LATICRETE® 3D Printing Mortar NW) and lightweight (LATICRETE® 3D Printing Mortar LW) 3D mortars.

Note that at 1 day, despite being 32% lighter, LATICRETE® 3D Printing Mortar LW has higher compressive strength (7.9 Vs. 5.9 MPa) as compared to the normal weight mortar. However, as the specimen aged and further hydration took place, the compressive strength of the normal weight mortar exceeded those of the lightweight (29 Vs. 27 MPa at 28 days). The lower compressive strength of the lightweight 3D mortar as compared to the normal weight version is attributed to the lower density of the aggregate [14, 15]. The difference in compressive strength however, is not significant (~7% difference at 28 days).

The durability assessment on the 3D printable mortars was conducted following ASTM C666 – Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing, Procedure A [16]. The test results indicated while LATICRETE® 3D Printing Mortar NW passed the test, LATICRETE® 3D Printing Mortar LW failed. Three cast-prims specimens (75 × 100 × 405 mm or 3 × 4 × 16 in.) of each type of mortars were tested. The average values of relative dynamic modulus of elasticity (RDME) are presented in Fig. 2.

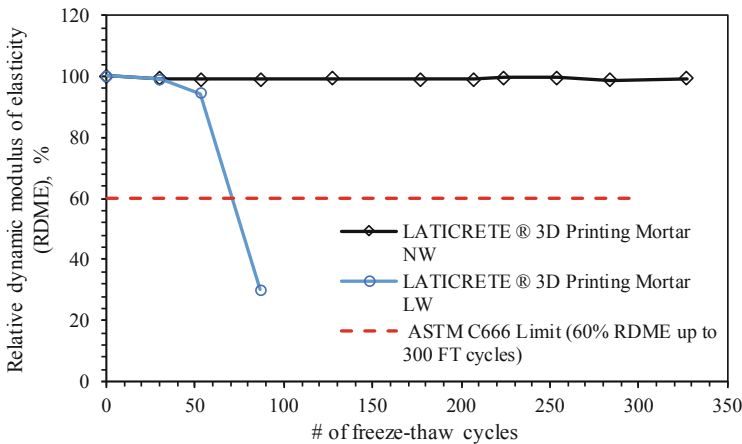


Fig. 2. RDME of 3D Printable Mortars

As presented in Fig. 2, the normal weight mortar remains intact even after more than 320 freeze-thaw (FT) cycles while the lightweight version failed after approximately 70 FT cycles. This indicates that the lightweight mortar is not suitable to be used in predominantly cold regions that see winter temperatures dropping below 0 °C.

2.3 Printability

The printability of the mortars is demonstrated by printing small-scale structures as shown in Fig. 3 by using a modified Ender 3 desktop 3D printer. The printer was modified in such that it deposits mortar rather than thermoplastic materials. One method is by replacing the thermoplastic extruder with a hose, which delivers the mortar from an extruder gun. From here, the hose attaches to the printer's printing

head. As the extruder gun pushes the material through the hose, the printer's head moves, and deposits the mortar layer-by-layer according to the designed code. The G-code used in this study is generated by using Slic3r slicing program in conjunction with Repetier-Host software. The printing process was completed within 5 min for each structure. Each filament is 8–12 mm wide and 5–6 mm high. As shown in Fig. 3, both mortars were able to be deposited layer-by-layer while holding their shape.

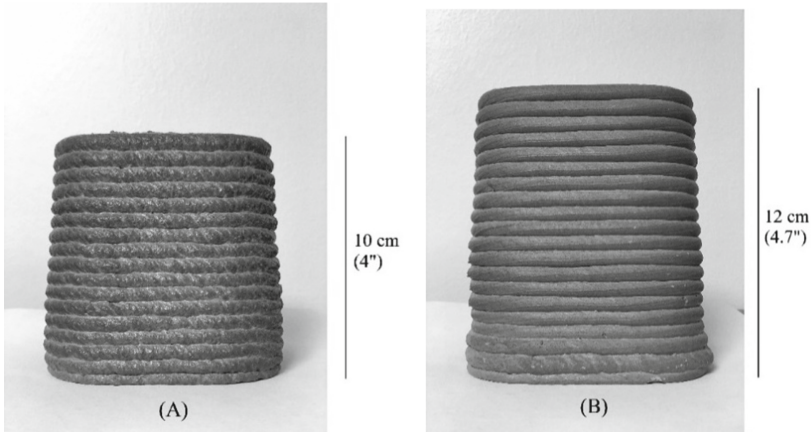


Fig. 3. Lab-scale 3D-printed structure: (A) LATICRETE® 3D Printing Mortar NW and (B) LATICRETE® 3D printing mortar LW

2.4 Interlayer Adhesion Tensile Test

The interlayer adhesion strength was assessed by testing printed specimens for tensile strength (perpendicular to the printing direction). Three types of specimens were tested for the interlayer adhesion strength: non-cold joint, treated cold joint, and untreated cold joint. For the non-cold joint, the specimens were printed continuously. Cold joints specimens were printed in two parts with a 24-h interval between the bottom and the top sections (see Fig. 4 (A)). The interlayer between the bottom section of the specimen and its upper section is defined as a cold joint. The cold joint is reported to be the weak point of the printed structure [17–22]. As an effort to improve the bonding strength, some of the cold joints were treated with a slurry of a thin-set mortar (i.e., LATICRETE® 254 Platinum thin-set mortar at a 23% water ratio per the mixing specification) in which, a thin layer of thin-set slurry was applied on the surface of the specimen before the upper part printing. This application was done using a metal spatula, applying approximately a 1 mm thickness to the top layer. Following this step, the 3D mortar was printed immediately following the application of the thin-set. These specimens are classified as a treated cold joint. Specimens with a cold joint, but without treatment (no thin-set applied on the cold joint), are classified as untreated cold joints. An example of the specimen is shown in Fig. 4 (A).

The epoxy that was applied on the side surfaces of the first three layers (top and bottom) of the specimen, as shown in Fig. 4 (A), served as the grip which holds the

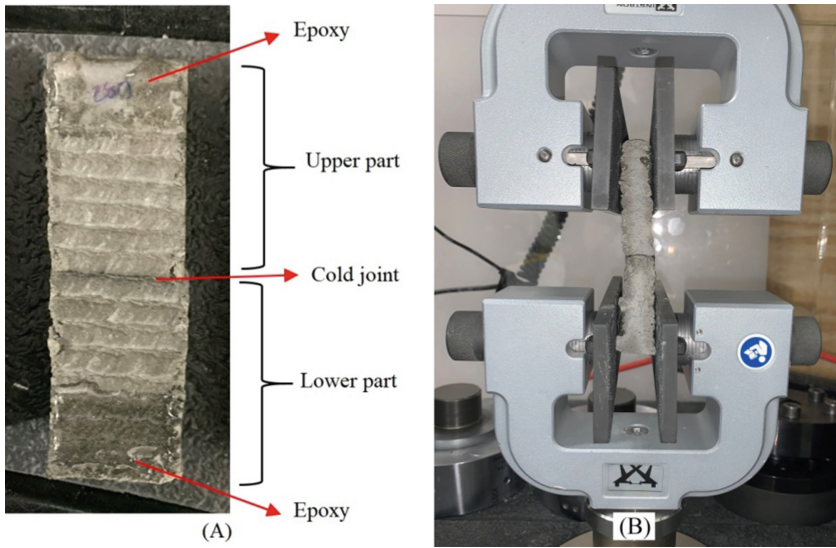


Fig. 4. (A) Interlayer adhesion test specimen; (B) Interlayer tensile adhesion test setup

specimen during testing. The adhesion interlayer test setup is shown in Fig. 4 (B). The rate of the tensile test was set at 5 mm/min. After the specimen broke, the area of the failure plane was measured. In all tested specimens, the failure plane occurred either at the cold joint or the non-cold joint interlayer. The interlayer tensile adhesion test results are presented in Fig. 5 and Table 2. Each data point presented in Fig. 5 is the average of 2–3 specimens.

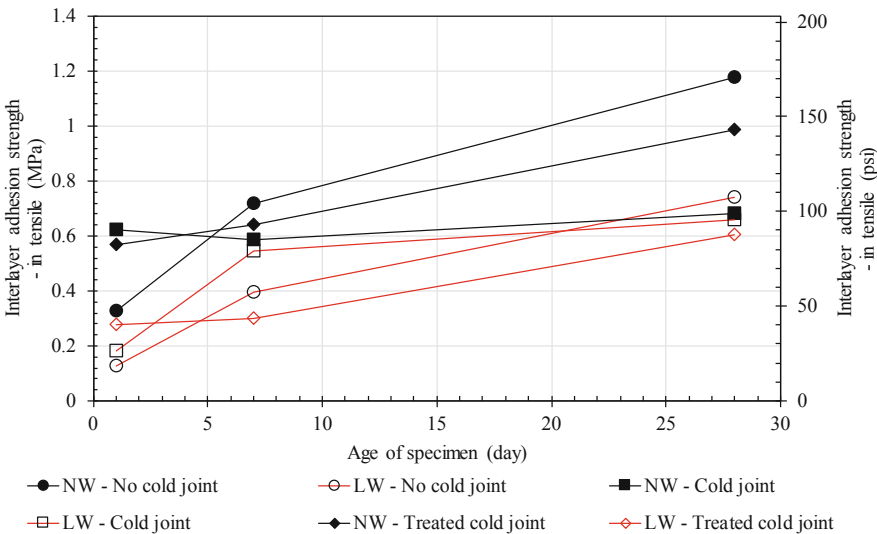


Fig. 5. Interlayer adhesion tensile strength test results

Table 2. The probability of tensile failure occurs at the cold joint

Specimen	Percent occurrence of failure at the cold joint	
	LATICRETE ® 3D Printing Mortar NW	LATICRETE ® 3D Printing Mortar LW
Treated	8.3%	0.0%
Untreated	91.7%	100.0%

NB: 12 specimens were tested for each case

The interlayer tensile adhesion strength increases as the specimens aged (the exception is on LATICRETE ® 3D Printing Mortar NW specimens where the 1-day tensile adhesion strength is higher than the 7-day measurement). For the normal weight specimens with a cold joint, after 7 days, show that interlayer adhesion strength is lower than the specimens without cold joint. The similar case on LATICRETE ® 3D Printing Mortar LW only happens on the 28-day specimens. The interlayer adhesion strengths of LATICRETE ® 3D Printing Mortar NW are higher than those of LATICRETE ® 3D Printing Mortar LW at all tested regimes.

Applying a thin layer of LATICRETE® 254 Platinum thin-set slurry on the cold joint before continuing the printing process improves the adhesion of the cold joint. This can be seen from the results presented in Table 2 where only 8.3% and 0% of the LATICRETE ® 3D Printing Mortar NW and LATICRETE ® 3D Printing Mortar LW treated specimens failed at the cold joints, respectively. In contrast, the majority of the untreated specimens failed at the cold joints (91.7% and 100% for LATICRETE ® 3D Printing Mortar NW and LATICRETE ® 3D Printing Mortar LW, respectively).

3 3D Printing Project

The LATICRETE ® 3D Printing Mortar NW was used to print a 3D-printed house in Dubai, UAE. COBOD's second generation BOD 2-3D printer was used for this project. The printing was executed by 3DVinci Creations. The dimension of the extruded mortar was 15 × 40 mm with printing speed ranges from 200–400 mm/s. The majority of the structure was printed in 2 layers (40 mm wide per layer), each folded unto each other creating an 80 mm thick wall. An example of a design sketch of the wall is shown in Fig. 6.

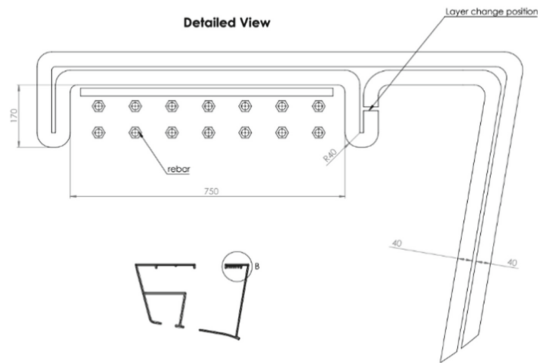


Fig. 6. A design sketch of part of the walls

The printed walls vary between 2.85–3.15 m in height (excluding parapets) with two layers of cold joints. Each cold joint is treated with Platinum 254 thin-set. Furthermore, the parapets were also printed by using the same material. A total of 131-h of printing was done to complete the 153 m² (1647sqft) structure. The model of the printed structure can be seen in Fig. 7.

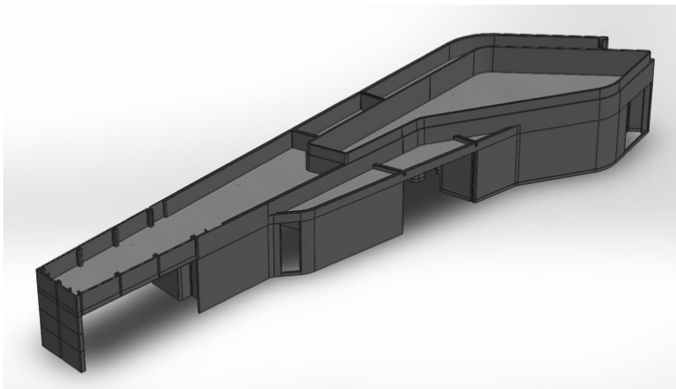


Fig. 7. The model of the 3D printed house

4 Conclusion

This manuscript provides insight on several important aspects of 3DCP. These aspects include the materials' properties (fresh, mechanical, and durability) and the printability of 3D printable mortars. Both mortars, LATICRETE ® 3D Printing Mortar NW and LATICRETE ® 3D Printing Mortar LW, have demonstrated their capacity to be used for 3DCP applications.

Acknowledgement. The authors would like to express their sincere gratitude to Douglas Hendrix and Dr. Kay Wille from the Department of Civil and Environmental Engineering, University of Connecticut for facilitating the ASTM C666 test.

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Interlayer Effect on Fracture Behavior of 3D Printing Concrete

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Abstract. Concrete additive manufacturing, also known as concrete 3D printing, opens new opportunities in the construction industry and architectural design. The layer-by-layer additive manufacture process introduces printing filaments and interlayers into the concrete components. How this new manufacturing process affects the fracture behavior of 3D printed concrete components has not been well understood. In this study, we characterized the fracture behavior of 3D printing concrete at printing interlayers in comparison with printing filaments. 3D printing concrete specimens containing notches at interlayer or filament locations were loaded in a servo-controlled testing system with closed-loop control through a high-resolution digital image correlation system that measures crack opening displacement and crack extension during loading. The plane-strain fracture toughness and critical effective crack length at the interlayer and the filament were experimentally determined. The results revealed that fracture toughness at the interlayer was 20–26% lower than at the filament. This indicates that compared with filaments, the interlayers under stress are more sensitive to defects and imperfections that can cause crack propagation and fracture failure. The results are important for understanding the effect of the 3D printing manufacturing process on the mechanical behavior of concrete components, paving the way for more rational analysis and design of highly loaded structures made of 3D printed concrete.

Keywords: Concrete · Additive manufacturing · 3D printing · Interlayer · Fracture toughness · Effective crack length

1 Introduction

Concrete additive manufacturing, also known as concrete 3D printing, opens tremendous opportunities in the construction industry and architectural design. The rapid, automated construction of concrete structures or components can reduce labor and material costs, remove cumbersome formworks, and allows construction in harsh and less accessible environments [1, 2].

Currently, concrete 3D printing technology is mostly being explored for residential housing [3–5], pedestrian bridges [6] and installation art [7, 8], but much less so in highly loaded structures. Our recent research has demonstrated that concrete 3D printing can enable the automated on-site construction of ultra-tall wind turbine towers (>140 m tall) for the renewable energy industry (Fig. 1). Large wind turbines benefit

from economies of scale from larger components such as taller towers but are constrained by transportation size and weight. Through onsite and automated additive manufacturing of wind turbine tower segments and assembly, this novel 3D concrete printing approach eliminates the transportation size and weight constraints for building low-cost ultra-tall turbine towers. It is estimated that 3D concrete printed towers can reduce tower capital costs by approximately 50% compared with conventional 140-m steel wind turbine towers, saving about \$700,000 per tower. 3D concrete printing also has potential for manufacturing low-cost offshore wind components in ports for offshore wind deployments. The combined technical resource potential of onshore and offshore wind energy in California alone is approximately 170 GW, possibly providing about twice the electricity needed in California [9, 10].

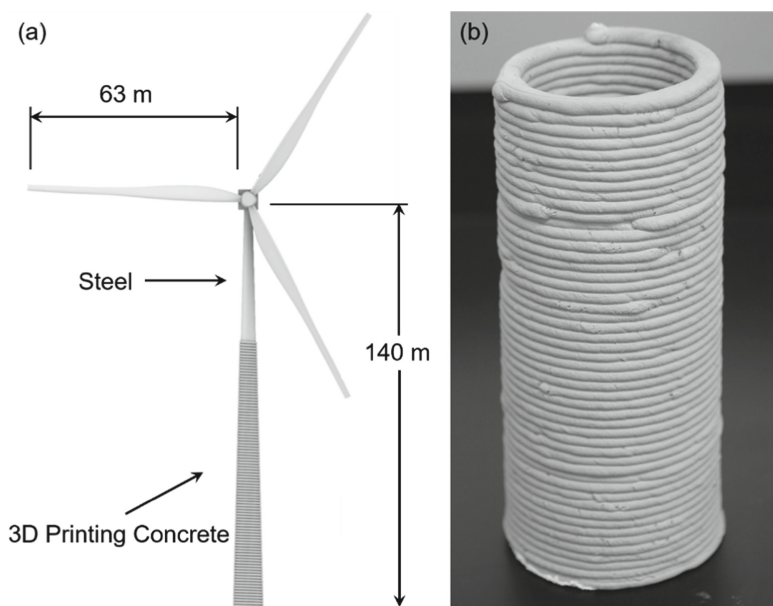


Fig. 1. Ultra-tall wind turbine tower additively manufactured on site: (a) example tower illustration, (b) 3D printed tower geometry at reduced scale.

In order to rationally analyze and reliably design such highly loaded structures such as tall towers made of 3D printed concrete, it is critical to understand the effect of the new manufacturing process on the mechanical behavior of 3D printed concrete components and structures. Different from normal cast concrete, the layer-by-layer deposition process introduces printing filaments and the interlayers between the filaments. The presence of interlayers might affect the fracture behavior of the structural components, subsequently impacting the durability, serviceability and even safety of the concrete structures manufactured through the 3D printing process. In order to understand such effect, this study experimentally characterized the plane-strain fracture toughness (K_{IC}) of 3D printing concrete filaments as well as interlayers. Fracture tests

under three-point bending were performed on notched beam specimens manufactured through 3D concrete printing along the beam height direction. Two different notch locations were investigated: inside the filament, and at the interlayer between two adjacent filaments. A closed-loop controlled testing system integrated with a digital image correlation (DIC) system accurately captured the post-cracking behavior of the specimens including crack extension and opening under loading.

2 Experimental Investigation

2.1 3D Printing Concrete Materials

Table 1 shows the two different mix designs of 3D printing concrete materials in this study. The cementitious material design focused on achieving an early-age rheology for the material to transmit through the pumping system to the nozzle head, and an early-age stiffness to retain shape under weight and pressure from the consequent layers [11, 12]. The mixtures contained water, a polycarboxylate-based superplasticizer, Type I ordinary Portland cement, silica fume (mean particle size = 150 nm), fine silica sand (mean grain size = 95 μm , max. grain size = 150 μm), ASTM C778-02 standard river sand (mean grain size = 1.2 mm, max. grain size = 2 mm), and Class F fly ash ($\text{CaO} < 3\%$) for 3DPC-I only. The water-to-binder ratio was 0.29.

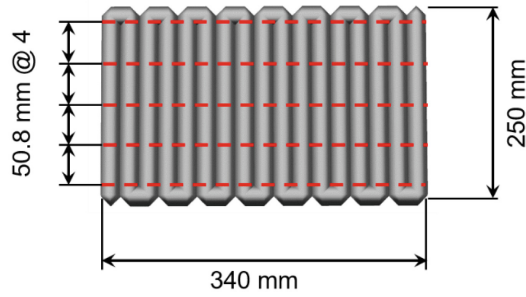
Table 1. Mix design of 3D printing concrete

Material	Cement	Silica fume	Fly ash	Sand	Fine sand	Water	SP	Water-to-binder ratio
3DPC-I	1	0.1	0.1	0.5	0.5	0.35	0.01	0.29
3DPC-II	1	0.2	—	0.5	0.5	0.35	0.01	0.29

2.2 3D Printing Concrete Specimen Preparation

The material mixing was conducted using a force-based Hobart mixer with 28.4-L capacity. First, all dry ingredients such as cement, silica fume, Class F fly ash and sands were dry-mixed for 5 min. Water and superplasticizer were then added and mixed for another 5 min to form a homogeneous mortar. The fresh mixture was then filled into an extruder installed with a SCARA robotic arm. The robot arm was controlled by G-code programmed to print a specimen with dimensions of $340 \times 250 \times 25.4$ mm. Each printing filament had the width of 20 mm and the height of 5 mm. The specimen was printed following a path shown in Fig. 2 (a) in a horizontal plane, and then the process was repeated vertically on top of each adjacent plane, containing six vertical planes in total. The printing speed was 20 mm/s and the total printing time was 25 min (Fig. 2 (b)).

After printing was completed, the printed specimen was further cut into smaller $304.8 \text{ mm} \times 50.8 \text{ mm} \times 25.4 \text{ mm}$ beam specimens by pressing sharp steel blades from the top into the specimen, along the beam length direction without disturbing the printing interlayers (Fig. 2 (c)). The beam length was perpendicular to the printing



(a) Specimen geometry



(b) 3D concrete printing process



(c) 3DPC beam specimens preparation

Fig. 2. 3D printed concrete specimens preparation.

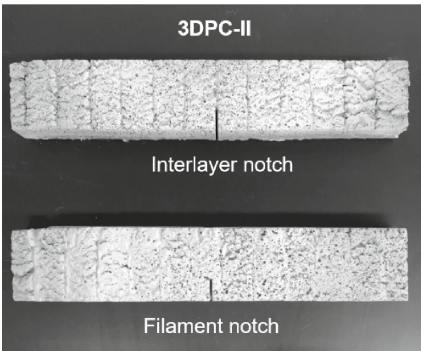
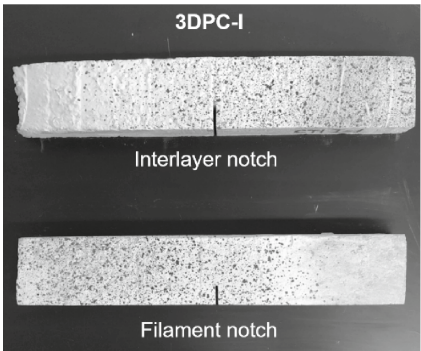


Fig. 3. 3D printing concrete fracture test specimens containing notches.

path. The beam specimens were then moisture-cured in laboratory environment under the temperature of 23 ± 1 °C for 28 days. Then, a saw-cut notch with width of 3 mm was created at two different locations in different specimens: (1) inside the filament, and (2) along the printing interlayer (Fig. 3). The notch-to-depth ratio was fixed at 1/3. The span-to-depth ratio was 4 [13].

2.3 Fracture Toughness Measurement of Concrete Printing Filament and Interlayer

To measure the fracture toughness K_{IC} of the printing filament in comparison with the interlayer, three-point bending test was conducted on notched beam specimens at the age of 28 days, with a procedure similar to ASTM E399 (Fig. 4) [14]. An MTS hydraulic testing frame was used to apply load under a closed-loop displacement control through a digital image correlation (DIC) system that provides non-contact and high-resolution measurement of 3D full-field displacement and deformation of the specimen (Fig. 5). Before testing, the specimen surfaces were painted white and then sprayed with a black-dot speckle pattern for DIC measurement. During testing, the loading rate was controlled by DIC to ensure a constant increasing rate of crack mouth opening displacement (CMOD) at 0.005 mm/min. During the fracture test, the CMOD, the deformation near the crack tip and crack propagation were measured by DIC, and the load was recorded continuously by the MTS system. The test was stopped after fracture failure when a crack propagated through the entire depth of the specimen.

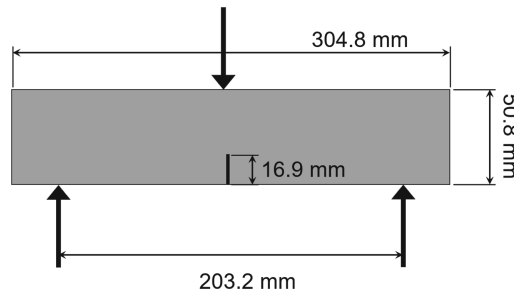


Fig. 4. 3D printing concrete fracture test specimen geometry.

3 Results and Discussion

Figure 6 shows the measured load vs. CMOD relations for the filaments and the interlayers in two different 3D printing concrete mixtures (3DPC-I and 3DPC-II). It is seen that each load-CMOD curve can be divided into three major stages: (1) initial elastic stage when the material compliance remained constant and the crack did not grow; (2) the crack growth stage I when a process zone started to grow in front of the crack tip. The process zone was bridged by aggregates and thus was not traction-free, representing a “fictitious crack” rather than a physical crack. During this stage, the load increased gradually but with reduced stiffness till a maximum process zone size was reached at the peak load; and (3) the crack growth stage II when the traction-free crack tip advanced with decreasing load. During this stage, the load kept decreasing during the propagation of the physical crack, eventually reaching zero when the crack propagated through the entire specimen.

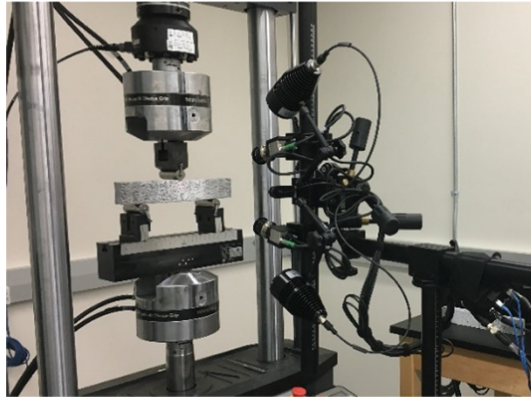


Fig. 5. 3D printing concrete fracture test setup

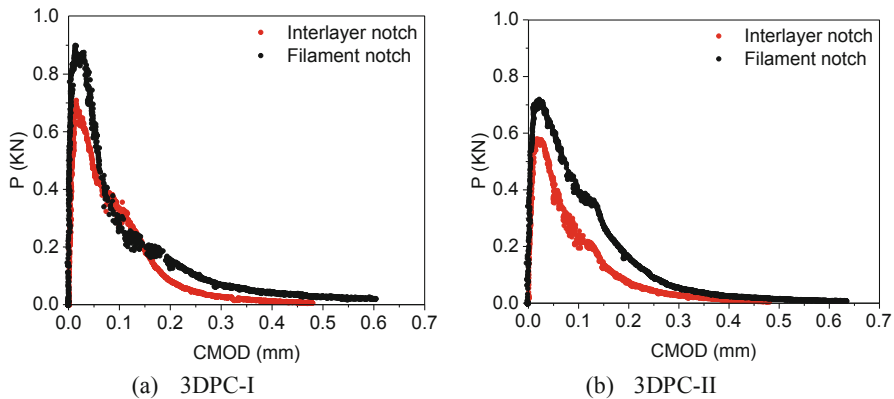


Fig. 6. Load vs. crack mouth opening displacement relation for 3DPC with different mix designs and different notch locations.

Figure 6(a) shows that for 3DPC-I, the peak load was lower in the interlayer than in the filament. The peak load for fracture was 0.71 kN at a CMOD of 0.016 mm for the interlayer, in comparison with 0.90 kN at a CMOD of 0.020 mm for the filament. The similar reduction was observed in 3DPC-II with a different mix design (Fig. 6(b)). The peak load was 0.58 kN at a CMOD of 0.016 mm for the interlayer, in comparison with 0.72 kN at a CMOD of 0.022 mm for the filament. The 20.4% and 23.9% reduction in peak load and the lower CMOD at fracture for both types of 3DPC suggested that the printing interlayers have lower K_{IC} than the printing filaments.

The plane-strain fracture toughness K_{IC} was calculated based on the peak load (Fig. 7) on the load vs. CMOD curve and the critical effective crack length (Fig. 8) measured by DIC [15, 16]. The critical effective crack length was defined as the initial

notch crack length plus the maximum process zone size at the crack tip [17, 18]. The process zone represents the inelastic displacement zone formed in front of the crack tip under stress, and its size was measured as the distance between the physical crack tip and the “fictitious crack” tip where the crack tip opening displacement decreases to 0.

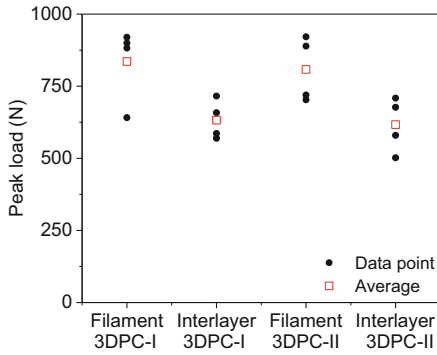


Fig. 7. Effect of notch location and mix design on peak load for fracture.

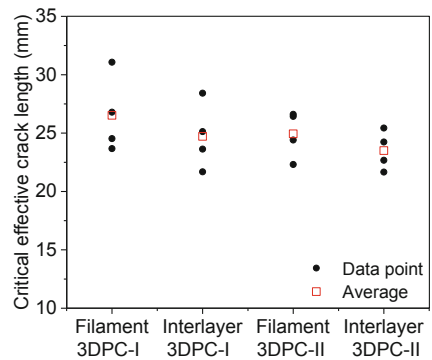


Fig. 8. Effect of notch location and mix design on critical effective crack length.

Figure 8 shows the critical effective crack length for the filaments and interlayers in two different types of 3DPC. It is seen that for each 3DPC, the interlayer tends to develop a shorter process zone at the crack tip before fracture compared with the filament. This indicates that the aggregate bridging plays an important role in the process zone size. Because the interlayers have less likelihood of larger aggregate (2 mm size) bridging at the crack tip, as the result of the layer-by-layer deposition process, a shorter process zone size can be developed before fracture. Furthermore, It is observed that different mix designs also affected the maximum process zone size and the critical effective crack length. For example, for the interlayer notch, 3DPC-II developed a shorter process zone than 3DPC-I. Same trend was also found for the filament notch. This indicated that besides aggregate bridging, the chemical bond of the cementitious binder at the crack tip also contributes to the process zone behavior. Different 3DPC mix designs would lead to different rheology and hydration kinetics, resulting in different chemical bonds at the crack tip either inside the filament or at the interlayer.

Figure 9 compares interlayer and filament K_{IC} values for two different types of 3DPC. For 3DPC-I, the interlayer K_{IC} was 25.4% lower than the filament K_{IC} in average. For 3DPC-II, the interlayer K_{IC} was 20.0% lower than the filament K_{IC} in average. In addition, fracture energy was calculated based on the load-displacement curve in Fig. 10 (a), and was defined as the energy release per unit area of crack propagation. The displacement was measured by DIC at the location of the middle loading point. Figure 10 (b) compares fracture energy for two different types of 3DPC. For 3DPC-I, the interlayer fracture energy was 21.1% lower than the filament fracture energy in average. For 3DPC-II, the interlayer fracture energy was 39.9% lower than

the filament fracture energy in average. The fracture energy as well as K_{IC} results suggest that in a 3DPC concrete component, the interlayers tend to have lower resistance than the filaments to crack propagation and fracture. The fracture behavior in 3DPC depends on two mechanisms: (1) the mix design, which affects early-age rheology and hydration kinetics, subsequently determining the chemical bond and the physical bond (e.g., due to interlayer roughness [19]) formed at the crack tip and influencing the process zone behavior; and (2) the aggregate size and bridging effect, which affects the process zone size at the crack tip before fracture occurs, causing significant difference of K_{IC} and fracture energy between the interlayers and the filaments.

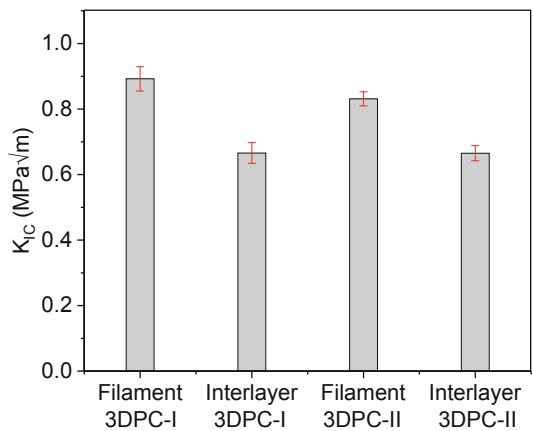


Fig. 9. Effect of notch location and mix design on K_{IC} .

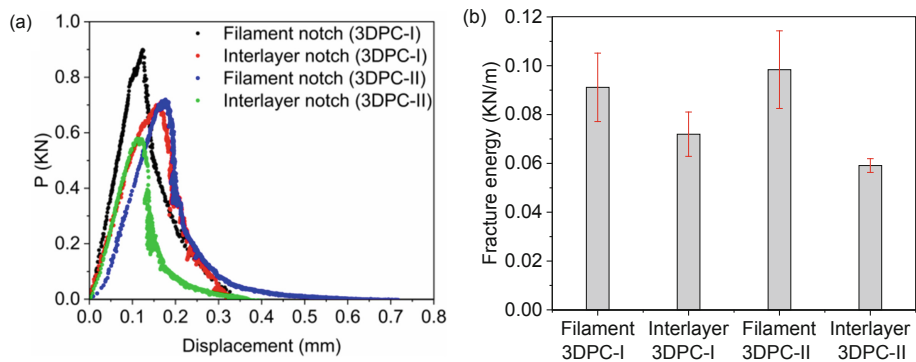


Fig. 10. Effect of notch location and mix design on fracture energy.

4 Conclusions

This study conducted fracture test to measure the plane-strain fracture toughness K_{IC} and critical effective process zone size of 3D printing concrete at two different notch locations (filament and interlayer) and with two different mix designs. The following conclusions are drawn:

- (1) 3D printing concrete interlayer had lower K_{IC} than the filament, suggesting that for a structural component manufactured by the 3D concrete printing process, the interlayers have lower resistance to crack propagation and fracture than the filaments.
- (2) The lower K_{IC} of the interlayer is due to the less of bridging of aggregates at the crack tip located at the interlayer compared with the filament, which leads to a shorter process zone size developed before fracture.
- (3) The K_{IC} of 3D printing concrete depends on two major mechanisms: (i) aggregate bridging effect, which causes discrepancy in K_{IC} and fracture energy at interlayer vs. filament locations, and (ii) chemical bonding at the crack tip, which depends on the mix design that determines early-age rheology and hydration process.
- (4) Different from the fracture behavior of normally cast concrete whose resistance to fracture has little dependence on the location of notch or stress concentration, the fracture behavior of 3D printing concrete strongly depends on the location of notch or stress concentration. The new additive manufacturing process will inevitably introduce interlayers into the concrete components, which can behave as weaker locations to resist fracture.

Acknowledgments. The authors gratefully acknowledge funding from California Energy Commission (EPC-17-023) for supporting this research.

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Auxetic Behavior of Cementitious Cellular Composites Under Uniaxial Compression and Cyclic Loading

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Abstract. Mechanical behavior of cementitious cellular composites (CCC) with auxetic behavior was investigated under uniaxial compression and cyclic loading. Three cellular structures with different geometrical parameters are designed and prepared by 3D printing technique. Meanwhile, plain mortar and fiber reinforced mortar are used as constituent material, respectively. Ductility of the constituent materials is evaluated by four-point bending tests. Uniaxial compression and cyclic loading tests are performed on the CCCs. Experiments show that with proper structure and constituent material, CCCs can exhibit auxetic behavior. For the tested CCCs (P25 and P50), negative Poisson's ratio is obtained: as a result, strain hardening behavior can be identified in the stress-strain curve under uniaxial compression. In addition, large reversible deformation under cyclic loading is obtained on P25 under cyclic loading. Hysteretic behavior in the stress-strain curve can be identified in a single cycle, which means that CCCs dissipates energy in each cycle. After 3000 cycles, the maximum load and energy dissipation of each cycle increased owing to the slip hardening behavior of the PVA fibers in the constituent material. Owing to the excellent energy dissipation property, these auxetic CCCs may be used for vibration resistance structures in the engineering practice in the future.

Keywords: 3D printing · Negative Poisson's ratio · Cementitious material · Cyclic loading

1 Introduction

Mechanical properties of composite materials are crucially influenced by both mechanical properties of the constituent phases but also the geometrical distribution features of these phases. Cementitious materials are multi-phase materials. Therefore, in the past several decades, numerous efforts have been done to configure, modify or tailor the geometrical distribution, which is more commonly referred as micro-structure, for better mechanical performance. For example, modifying the pore structure [1], modifying the air void structure [2, 3] and introducing new phases as reinforcement [4, 5].

Recently, as the rapid development of digital fabrication techniques, materials with tailored geometrical meso-structure have attracted much attention. On one hand, the tailored geometries can give the material excellent mechanical properties such as high fracture toughness [6, 7] and relative strength [8, 9]. On the other hand, tailoring the spatial distribution of constituent phases also enables one more dimension of freedom of materials design: not only design the constituent material property but also the structural response. For cementitious materials, taking advantage of the ability of 3D printing technique to fabricate complex geometries to produce cementitious cellular materials with tailored meso-structure might also be promising. Together with proper constituent material mix design, unprecedented mechanical properties of cementitious materials could be achieved.

Previously, cementitious cellular composites (CCCs) with negative Poisson's ratio were reported by [10, 11], in which cementitious specimens with cellular structure were prepared with the aid of 3D printing technology. However, the influence of structure features and constituent material properties on the compressive behavior of the CCCs were not fully studied. In this work, a similar cellular structure was adopted from [10, 11]. Molds for casting cementitious materials were digitally fabricated by 3D printing. CCCs with different cellular structures were obtained. Meanwhile, different mix proportions were used as constituent materials. Ductility of the constituent material was determined by four-point bending test. Mechanical properties of the CCCs were tested under uniaxial compression and compressive cyclic loading. The influence of constituent material ductility and cellular structural design parameters on the compression and fatigue behavior of the CCCs is analyzed.

2 Materials and Methods

Three types of cellular geometries were used in this study, two were adopted from [10]. Single unit of the cementitious cellular composites (CCCs) and the dimension of a specimen was shown in Fig. 1. The CCCs specimen is consisted of duplicate single cells. Geometrical parameters are listed in Table 1.

Table 1. Specimen groups with different design parameters

Specimen groups	Major axis "a" (mm)	Minor axis "b" (mm)	Volume (cm ³)
P0	4	4	63.7
P25	5	3	67.7
P50	6	2	79.8

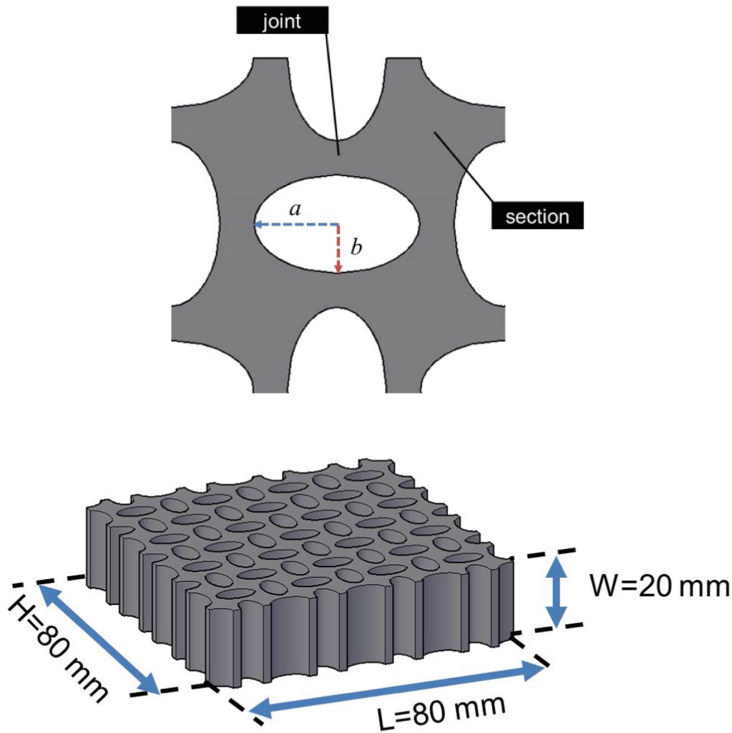


Fig. 1. Design parameters of cementitious cellular composites

2.1 Casting and Curing

The same method described in [10, 11] was adopted to prepare cementitious cellular composite specimens: cellular negative molds were prepared with the aid of 3D printing by a commercial fused deposition modelling (FDM) based 3D printer Ultimaker 2+ and the CCCs were prepared by the negative molds. A same fiber reinforced mortar was used as [11] to be constituent material for the cellular structure. The mix proportion is listed in Table 2.

Table 2. Mix proportion of constituent materials (kg/m³)

CEM I 42.5 N	FA	Sand	Water	SP	VA	PVA fiber
471	556	385	428	0.86	0.3	25.6

Dry components: CEM I 42.5 N, fly ash (FA), sand (0.125 μm –0.25 μm), VA (methyl-cellulose viscosity modifying agent) were weighed and mixed for four minutes using a Hobart machine. Afterwards, weighted superplasticizer and water were added, followed by 2 min mixing. Then fibers were added and mixed for another 2 min. The

mixed fresh mortar was casted into molds and vibrated for 40 s. Covered by plastic film, the specimens were stored in room temperature. After one day, the specimens were demolded and transferred to a curing chamber (20 °C, 96% RH) until 28 days age. Two types of specimens were casted, the CCCs were casted using the negative molds prepared by 3D printing and then tested in uniaxial compression at 28d. Bar specimens were casted using Styrofoam molds and tested in four-point bending at 28d.

2.2 Mechanical Tests

Specimens were taken out of the curing chamber before testing. All mechanical tests were done by a hydraulic press INSTRON 8872 at a loading rate of 0.01 mm/s. Load and displacement were measured and recorded during the tests. Images were taken during testing by a camera which was placed in front of the specimen. For the four-point bending test, displacement at the mid span is measured. A schematic of the four-point bending test is shown in Fig. 2.

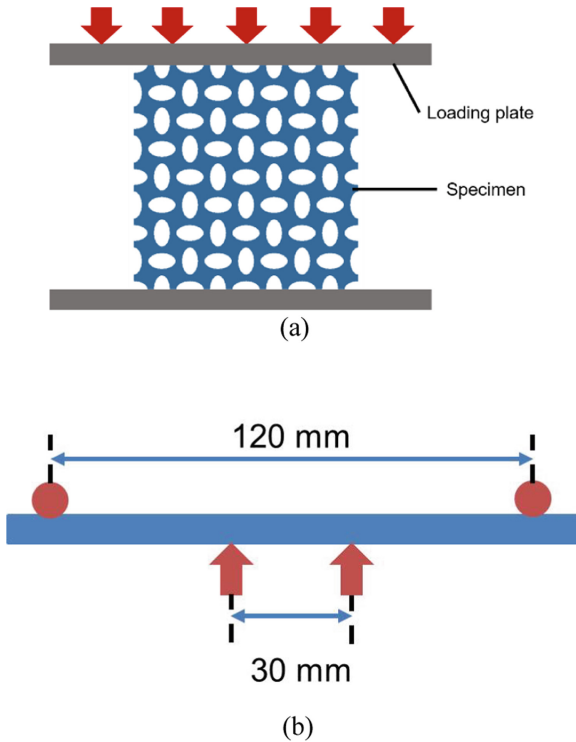


Fig. 2. Schematics of a) uniaxial compression and b) four-point bending test

3 Results and Discussion

3.1 Ductility of Constituent Material

As mentioned before, global mechanical properties of cellular materials are dictated by both its constituent material properties and the structural configuration. Therefore, coupled analyses of the constituent material properties and the structural features of the CCCs helps understanding of the mechanism of the auxetic behavior.

The flexural-deflection curves of plain mortar and fiber reinforced mortar are shown in Fig. 3. As expected, the plain mortar exhibits a rather brittle response: a rapid drop after the peak load can be found, indicating a rapid failure of the loaded specimen. Similarly, as the same cementitious matrix was used, plain mortar and fiber reinforced mortar have similar cracking strength at the first peak. However, after the first peak fiber reinforced mortar shows ductile stress-strain response: instead of rapid failure, due to the crack bridging behavior of the incorporated PVA fibers, load started to increase and a secondary peak can be found. Owing to the secondary peak, the ductility of fiber reinforced constituent material is much higher than plain mortar which enables the cellular structure to exhibit auxetic behavior, which will be discussed in detail in the next part.

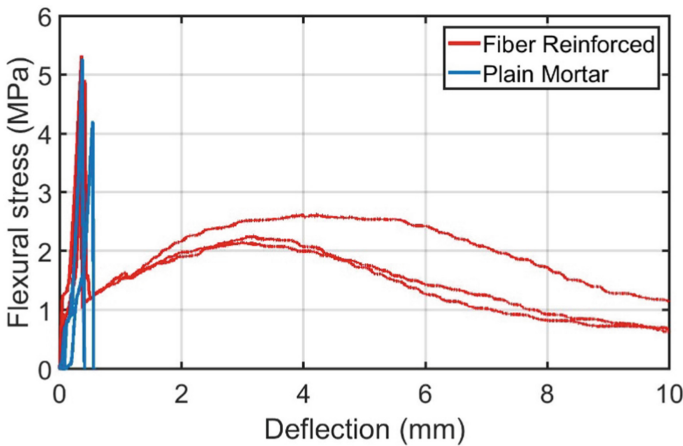


Fig. 3. Flexural-Deflection curves of constituent materials, several results are adopted from [11]

3.2 Compressive Behavior of the CCCs

Figure 4 shows the stress-strain curves of cellular structure P25 with plain mortar as constituent material. Brittle fracture was observed during the compression tests: after the peak load was reached, micro cracks rapidly started to localize and eventually lead to the failure of the compressed specimen, witnessed by a sharp drop in the load-displacement curve. Owing to the cellular structure, in some cases cracks developed through the cellular structure layer by layer so that multiple sharp drops can be found in the load-displacement curves.

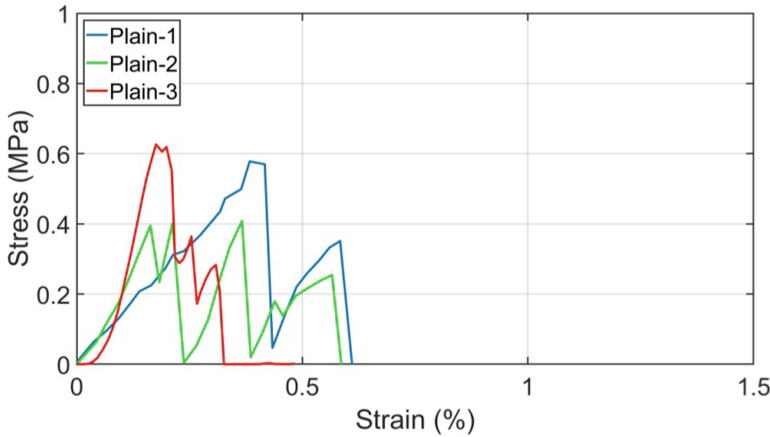


Fig. 4. Stress-strain curves of P25, data is adopted from [11]

On the contrary, when fiber reinforced mortar was used as constituent materials rather ductile damage process can be witnessed from the stress-strain response (see Fig. 5, P25), which can be roughly divided into three stages, marked in the load-displacement curves.

In the first stage (approximately from 0% strain to 11% strain), the mechanical response under compression is similar to that of traditional cementitious materials: an ascending branch can be found when external load imposed. After the elastic regime micro cracks started to initiate, as soon as peak load was reached (around 1 MPa), micro cracks started to localize at the joints of each single cell of the specimen. Because fiber reinforced mortar was used as constituent material, crack bridging allowed those localized small cracks at the joints to open slowly as compression went on instead of a rapid rupture. As a result, the sections of each single cell started to rotate. Meanwhile, lateral contraction could be observed during the test, namely auxetic behavior was achieved in this stage.

In the second stage (from 11% strain to 40% strain), the cellular structure was generally destroyed and compacted to be “solid” constituent material. As can be seen from Fig. 5, the hollow ellipse structure was compressed to deform and shrink, exhibiting more contraction in the lateral direction when the vertical compression continued. Correspondingly, in the stress-strain curves a compressive strain hardening behavior witnessed by a load increase after the first peak in previous stage because the cellular structure was destroyed and generally compacted. Similar strain hardening process can be also found in other auxetic materials [12, 13]. After the second peak (around 3 MPa) cracks started to initiate and localize in the sections of single cells then eventually developed in shear crack planes, witnessed in the stress-strain curves by a descending branch after the secondary peak. In this sense, this secondary peak is quite similar to the typical compression process of a conventional fiber reinforced cementitious material.

The third stage (after 40% strain) is a pure compacting process of the crushed constituent material which leads to rapid stress rise because the materials were compacted denser.

According to the hypothesis in [11], the auxetic behavior of the CCCs can be dominated by both constituent material properties as well as the cellular chirality. In this study, a same mix as [11] was used, the influence of constituent material was eliminated. In this case, obvious impact of cellular geometrical features on overall compression behavior of the CCCs can be identified. As can be seen from, P0 doesn't show auxetic behavior because of the symmetrical geometry of the section, comparatively, P50 shows similar auxetic behavior as P25. Meanwhile, from the stress-strain curves P50 shows similar three-stages response as P25: after the first peak load increased again because the cellular structure was destroyed and compacted. Because the volume of P50 (79.4 cm^3) is higher than P25 (67.8 cm^3), the peak load at the secondary increase is also higher. As for P0, the entire compression process was rather similar to that of conventional fiber reinforced materials, namely one peak can be found and afterwards a long descending branch can be found because of the ductility from constituent material.

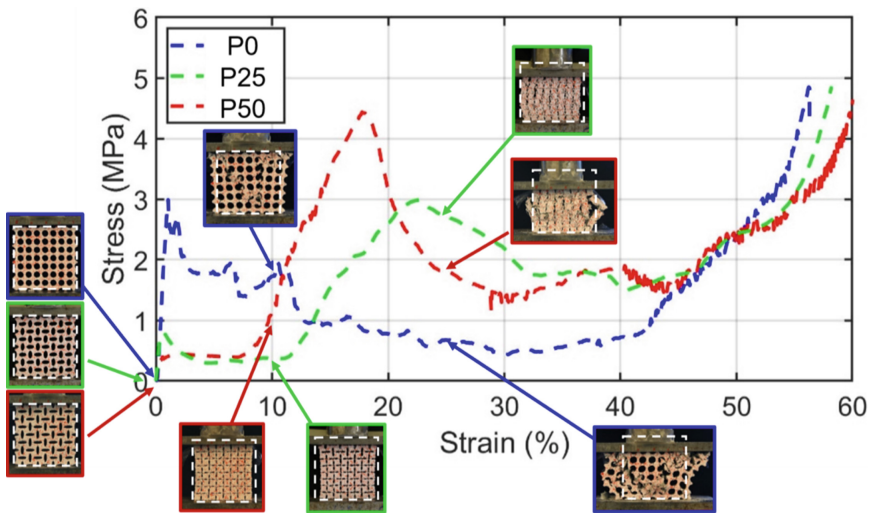


Fig. 5. Stress-strain curves of the CCCs and corresponding compressed specimens, several curves and pictures are adopted from [11, 14]

A stress-strain curve of P25 under one cyclic loading (the 3000th cycle) is shown in Fig. 6. Typical hysteresis behavior can be found from the curves (from 11.25% to 13.75% of strain): the loading and unloading branch do not completely overlap in one cycle. After 3000 cycles, the maximum load increased slowly with the cycle number increasing (from 0.1 MPa to 0.14 MPa, see Fig. 7). Similar trend can be also observed from the specific dissipated energy in one cycle (calculated by the area surrounded by the loading and unloading branch in each cycle divided by the specimen volume, see Fig. 8). According to previous studies [15, 16], the crack bridging ability of PVA fibers comes from slip-hardening behavior when fibers are pulled out from cementitious

matrix. The slip-hardening behavior can be explained by fibrillation phenomenon of PVA fiber, which means that under external load molecules of PVA polymer stretch out from a single PVA fiber increasing surface roughness of the PVA fiber, increased the friction between PVA fiber and cementitious matrix. Similarly, under cyclic loading fibrillation may be much more severe [17] and more jamming friction may be the reason of load and energy dissipation increase after 3000 cycles. In general, the developed CCC possessed pseudo-elasticity of 2.5% reversible strain even until 20000 cycles, which means that the CCC is a promising energy dissipating material.

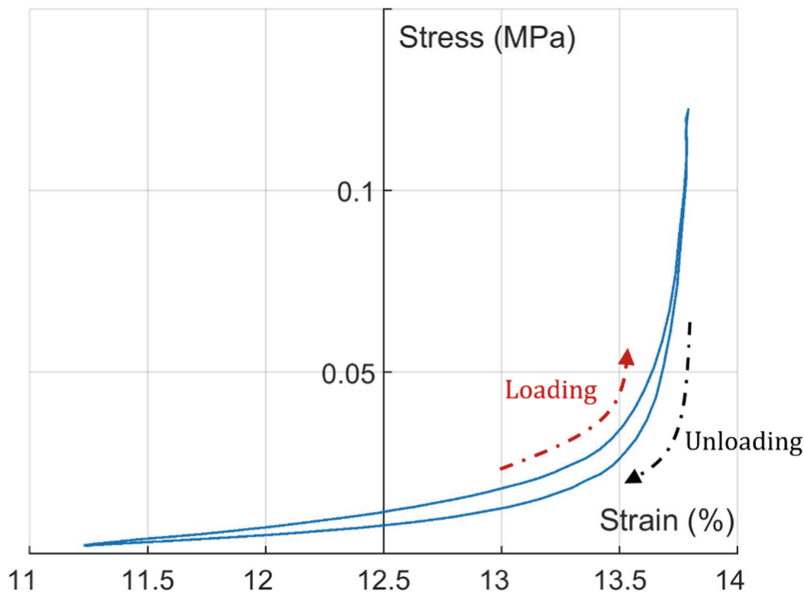


Fig. 6. Stress-strain response of the P25 at the 3000th cycle, data is adopted from [11]

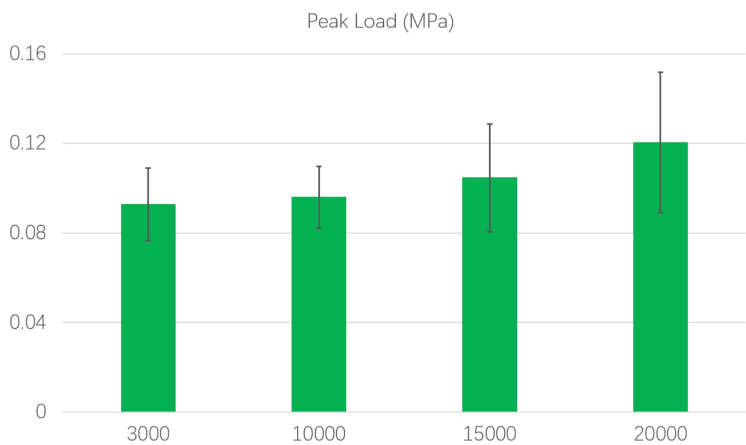


Fig. 7. Development of peak load in one cycle with number of cycles, standard deviation is indicated, several data is adopted from [11]

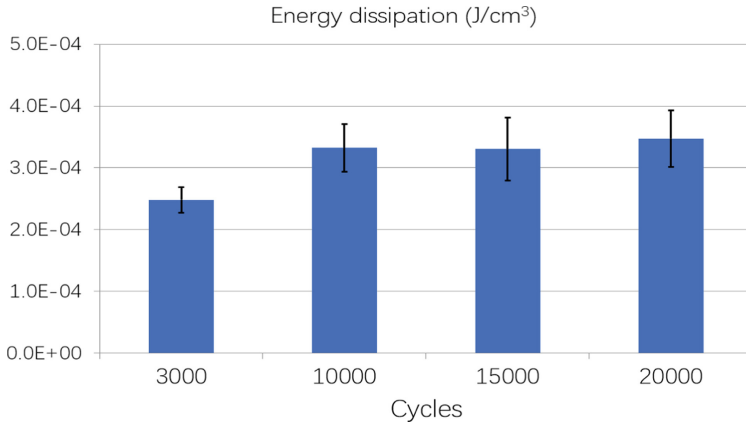


Fig. 8. Development of energy dissipated in one cycle with number of cycles, standard deviation is indicated, several data is adopted from [11]

4 Conclusions

In the present work, cementitious cellular composites (CCCs) with auxetic behavior are developed using 3D printing. The mechanical properties of CCCs are evaluated under uniaxial compression and cyclic loading. Influence of constituent materials and structure design parameters on the mechanical behavior of the CCCs are studied. Characteristics of auxetic CCCs under cyclic loading were measured. Based on the obtained experimental results several conclusions can be drawn:

- Both constituent material property and geometrical structure determine the overall compressive behavior of the CCCs. On one hand, the crack bridging ability of constituent material (fiber reinforced mortar) enables the CCCs exhibiting auxetic behavior; On the other hand, chirality of the sections in each single cell is required for cellular structures to show auxetic behavior.
- Under uniaxial compression, auxetic behavior was witness in P25 and P50 specimens. Owing to the auxetic behavior, P25 and P50 shows strain hardening behavior under compression: a secondary peak exists after the first peak.
- For the developed CCC (P25), a pseudo-elastic regime is found between 11.25% ~13.75% strain (in total 2.5% compressive deformation) under 20000 cycles, within this regime P25 shows flexible behavior and excellent energy dissipation property.
- The fatigue process of P25 under cyclic loading exhibit recoverable damage: after 3000 cycles, owing to the fibrillation of PVA fibers the maximum load increases leading to an increase in energy dissipation in each cycle until 20000 cycles. The increase of maximum load and energy dissipation implies that CCC is possible to be used as promising vibration resistant material.

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Impact of Particle Size and Grading on Aggregate-Bed 3D Concrete Printing

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Abstract. This research aims to investigate the effects of different parameters involved in particle-bed concrete printing on the quality of aggregate-bed concrete printing products. In particular, particle size and grading of aggregates were investigated by adopting two groups of single-size aggregates and a group of mix-size aggregates. The printed products were characterized by mechanical performance, CT scanning and visual appearance. The result reveals that the 3D printed products have layered structures, which is different from conventional casting concrete. The mechanical properties and macrostructure of printed specimens were significantly influenced by the adopted aggregate size and grading.

Keywords: 3D concrete printing · Aggregate-bed · Processing · Mechanical performance · Macrostructure

1 Introduction

Particle-bed printing is one of the trending 3D concrete printing methods in which binder liquid is sprayed or deposited into particle bed in each layer to selectively bind the granular material. Compared with other additive manufacturing technics, this processing method has almost no restrictions on the structure, enabling the possibility of building structures of any shape based on requirement without extra cost in formwork.

Particle-bed printing can usually be divided into two categories. One of them is using water-admixture mixtures as binder liquid to activate cement hydration in the bed, which is called selective binder activation. The other one, selective paste intrusion, is using binder paste to selectively fill the voids within particle packing to bind the particles [1].

Compared with selective cement activation, selective paste intrusion can significantly reduce the long construction time, which is more suitable for large-scale application. This is because, in this processing method, the height of each layer is much larger than that in selective cement activation, which in turn significantly reduces the number of layers. The height of each layer is highly depended on the particle size in the particle bed and the rheology of paste [2].

In recent research, the particle used in the bed is still limited to fine particle (cement, filler and fine sand) [3–5], offering a high geometrical accuracy but high manufacturing time and cost. To extend the use of particle-bed printing, the authors have developed a viable aggregate-bed printing scheme in previous research [6], using locally sourced aggregate as the particle bed to expand the adoption of particle-bed printing in the construction industry. In this paper, the effects of different sizes and grading of aggregates on printing quality in aggregate-bed printing will be investigated.

2 Materials and Methods

2.1 Materials

Ordinary Portland cement, conforming to Australian Standard AS3972, and densified silica fume from Ecotech was used as dry material in this study. Superplasticiser (MasterGlenium SKY 8379) and viscosity modifying agent (VMA, MasterMatrix 362) were used as admixtures to achieve the desired rheological properties. The mix proportion was referred to the previous study [6] and shown in Table 1.

Crushed limestone with a 7 mm normal maximum size was used as aggregates. Before the tests, a washing process was implemented to avoid the influence of the surface dust of aggregates. The grading of aggregates used in this study was shown in Fig. 1. Besides, two single-sized batches of aggregates retained on the 4.75 mm (no. 4) and 2.36 mm (no. 8) sieve but passed the sieve one size higher than the specified sieve, were used.

Table 1. Mix design (by weight) of the paste used in this study

Cement	Silica fume	Water	Superplasticiser	Viscosity modifying agent
1000	50	350	3	10

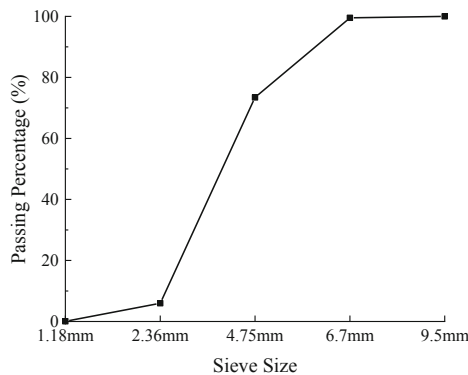


Fig. 1. Coarse aggregate gradation curves

2.2 3D Printing Process

Figure 2 illustrates the aggregate-bed concrete printing process and Fig. 3 shows the printing set-up used in this study. There are several repeating steps as described below.

- Firstly, aggregates were evenly spread onto the base of the build plate;
- Then, a blade swept along the printing path to control the height of aggregates, and excess aggregates were swept away;
- Once an aggregate layer was completed, the paste was extruded from the paste feeder through the nozzle on the printhead;
- Repeating the described steps above until the final product was printed.

The height of aggregates and paste applied in each layer were denoted as $h_{\text{aggregate}}$ and h_{paste} , respectively. In this study, both $h_{\text{aggregate}}$ and h_{paste} were set as 7 mm. The time gaps between the time of applying aggregate and paste were strictly set as 100 s.

After the printing process, the printed products were kept in the aggregate bed, and plastic sheets were used to cover the aggregate packing to prevent the water evaporation. After 24 h of hardening, the samples were taken out from the aggregate packing, and unbonded aggregates were recycled for future printing. The samples were immersed in water for further curing until the day of testing.

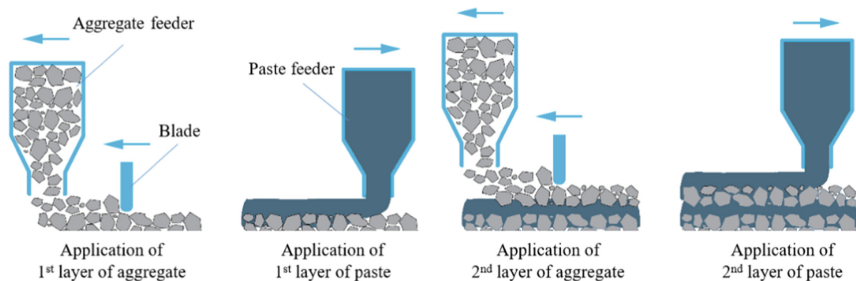


Fig. 2. Illustration of Aggregate-bed concrete printing process [6]

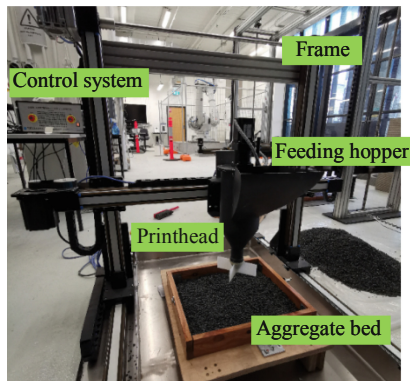


Fig. 3. Aggregate-bed concrete printing set-up

2.3 Test Specimens

Strip samples with dimensions of $50 \times 50 \times 600$ mm were printed, removed from the aggregate bed after 24 h and cured in 24°C water tank until the day of testing. Both compressive strength and flexural strength were tested at the age of 7 days. One day before each test, the samples were cut into a specific dimension, as shown in Fig. 4. In addition, plaster was applied at both the top and bottom surface to make them parallel to avoid any eccentricity.

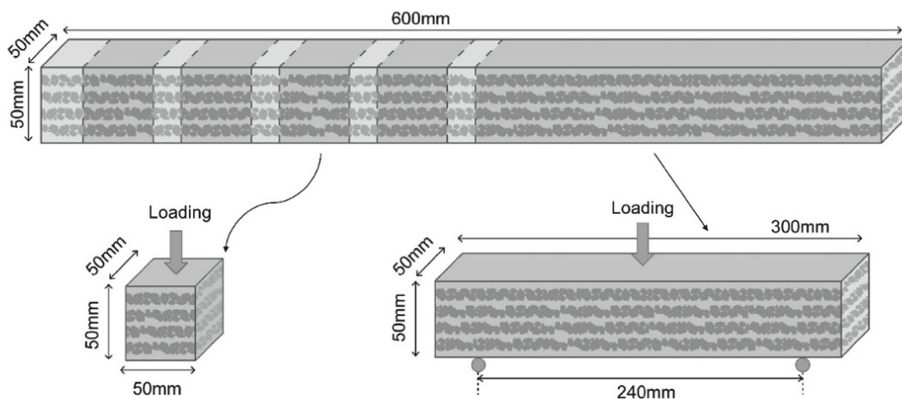


Fig. 4. Cutting diagram and testing direction for compressive and flexural tests

3 Results and Discussion

3.1 Mechanical Performance

The mechanical performances, in terms of compressive and flexural strength, are shown in Fig. 5. It is noticed that these three groups achieve an acceptable strength after 7 days, e.g. 4.1–4.6 MPa for flexural strength and 37.2–46.0 MPa for compressive strength. The strengths of printed samples are comparable to traditional concrete [7], enabling its great potential in engineering construction.

It can be noticed that the strengths of samples with 4.75–6.7 mm aggregates are the highest in both compressive and flexural strength. This is because the absence of small particles in this group makes more void within the aggregate bed during the printing, as depicted in Fig. 6. Simultaneously, the sizes of the voids among the aggregates were increased in this group. Therefore, the penetration depth of cement paste into the aggregate was improved. Consequently, better bonding between each layer can be achieved. Different from conventional casting concrete where a good grading of aggregate is preferable, single-size aggregates with large particle size are more suitable for aggregate-bed concrete printing. However, the shape accuracy of printed products is highly dependent on the maximum size of aggregates adopted. Hence, a dilemma between shape accuracy and mechanical strength exists and need to be solved based on construction requirements.

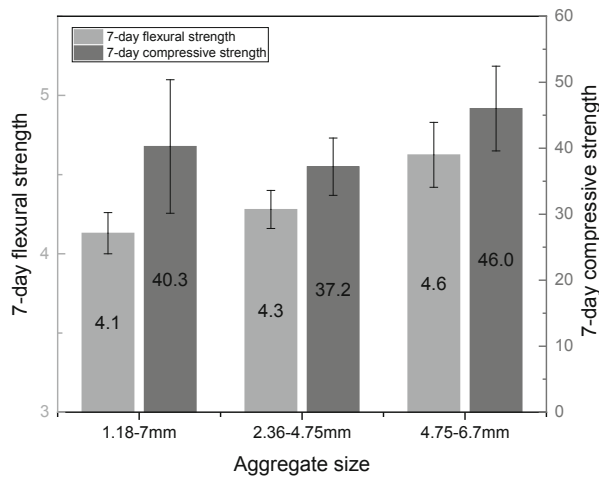


Fig. 5. Mechanical strengths of printed specimens at the age of 7 days

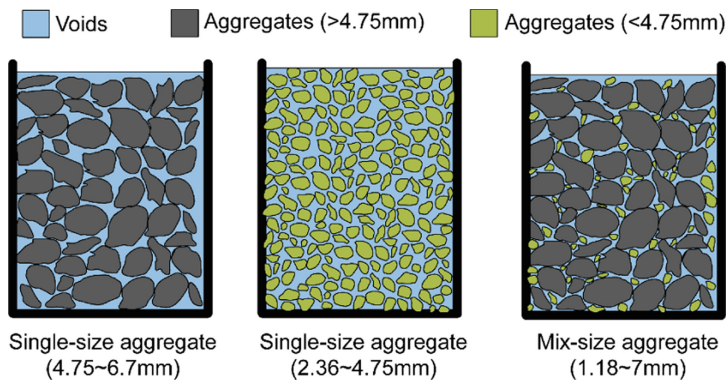


Fig. 6. Decrease in void content in mixed aggregate size

3.2 Macrostructure

Figure 7 shows a sample cut from printed products with a dimension of 40 mm × 40 mm × 40 mm. It was observed that aggregates and cement paste overlapped each other, forming a distinct layered structure. Most of the voids agglomerated at the vicinity of aggregates and some of them were even connected, which may eventually contribute to a ‘weak zone’ inside the sample. In addition, more voids were found along the edge of the printing direction compared with that in the middle. This is because, during printing, the paste spread from the middle to the two sides and the flow might stop earlier or later at some location due to the irregular void distribution of aggregate. The more voids provided by the aggregate, the less can the cement paste spread perpendicular to the printing direction. Therefore, the shape accuracy was reduced, and some voids were remained unfilled due to this flowing mechanism.

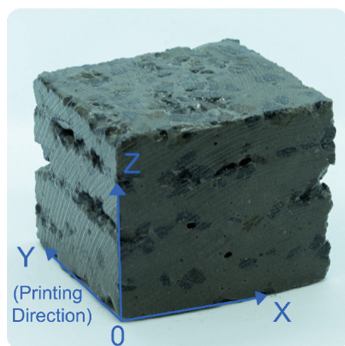


Fig. 7. Appearance of sample cut from printed product

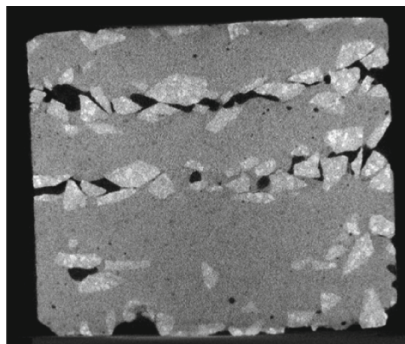


Fig. 8. Cross-section of printed product

3.3 Cross-Section Analysis

A typical cross-section of printed products was extracted using X-ray computed tomography (CT) technic, as shown in Fig. 8. It was noticed that the voids in the upper layer were more than that in the lower layer. One of the potential reasons could be the increase of yield stress and viscosity of cement paste along time during the printing process. The cement paste with higher yield stress and viscosity experiences more difficulty in penetrating into the aggregate packing [2]. Another reason might be that the gravitational pressure from the upper part may compress the lower part to achieve a denser structure. This phenomenon also happened in some extrusion-based 3DCP cases [8, 9].

It should also be noted that, as depicted in Fig. 8, the number of aggregates in the lower part was less than that in the upper part. This is because when the blade swept across the applied aggregates, some of the aggregates were carried away due to their angular shape, whilst some of the aggregates were squeezed into a lower position. Then, the cement paste below was ‘pushed away’ by these squeezed aggregates, and therefore extra space was made for more aggregates. Due to a cumulative effect of several layers of cement paste, there would be more aggregate existing in the upper layer. Nevertheless, this cumulative effect could be alleviated because the cement paste was getting hardened along time, which increased the ability of deformation resistance.

4 Conclusions

The aim of this research was to investigate the effects of particle size and grading of aggregates on the quality of aggregate-bed concrete printing products. The printed product had a different characteristic compared with conventional casting concrete.

- 1) Contrary to conventional casting concrete, single size of aggregates is preferable to achieve better mechanical performance. Samples made by a larger size of

aggregates exhibit a higher mechanical strength. However, the shape accuracy may be reduced with the increase of aggregates size.

- 2) The printed product had a highly layered structure. The ‘weak zone’ in the printed product was the voids found mostly at the vicinity of aggregates caused by the horizontal spreading and incomplete vertical penetration of cement paste.
- 3) The aggregates in the lower part were found to be less than that in the upper part. This was due to the deformation of the cement paste below, which made more space for aggregates in the upper part.

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Drying of 3D Printed Mortar Filaments at Early Age Assessed by X-Ray Computed Tomography

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Abstract. 3D extrusion-based additive manufacturing is known as the most widely applied printing strategy for digital fabrication of civil engineering materials. This construction method does not only require specific rheological properties and structural build-ups rates, but also mechanical properties comparable to conventional materials. In the current work, manually cast mortar filaments consisting of cement paste and glass beads are used to mimic the 3D printed cement-based materials. We first compare the 3D tomography of mortar between sealed and dried conditions with or without mold constraint at early age. We then carry out the 3-point-bending tests for sealed and dried mortar. Our results suggest that at very early age before setting, drying phenomena induce irreversible microcracks which lead to a deterioration of mechanical strength of the filaments.

Keywords: X-ray computed tomography · Drying · Cracking · 3D printing

1 Introduction

3D printing technology has been widely used in various research fields, it has a huge impact on traditional production and has become a creative manufacturing technique that might change the mode of future life [1–4]. This technology is increasingly being incorporated into the field of building construction [5–7].

Extrusion based additive manufacturing is the dominant technology for concrete printing projects [7, 8]. This technology is based on layer-by-layer extrusion of concrete filaments during which the shape of the printed element is strictly controlled.

It is known that the drying of the printed filaments may lead to detrimental consequences of the machinal properties when they are exposed in dried environment [5, 7]. This mechanical deterioration finds its origin at the drying front between the interlayers and leads to a decrease of the bonding strength for smooth layer surfaces. However, since the drying process intimates the loss of matter (mainly water in the case of concrete drying) inside of the element, an internal microstructure weakening may also occur which impacts the strength of the structures.

In the current study, we mainly focus on the impact of drying on the microstructure and the mechanical strength of one mortar layer. In order to accurately reflect the drying phenomena induced evolution of material properties, we first establish a one-dimensional model configuration with one face of the fresh filament exposing to drying. We then compare the 3D tomography of mortar between sealed and dried conditions, and with or without mold constraints at early age. We moreover carry out 3-point-bending tests for sealed and dried mortar. Our results suggest that at very early age before setting, drying phenomena induce irreversible microcracks which lead to a deterioration of the mechanical strength of the filaments.

2 Materials and Methods

2.1 Materials and Mix Proportions

A CEM I Cement with a specific density of 3.15 is used in this study. The Particle Size Distribution (PSD) of the powder is measured using a laser particle size analyzer (Malvern Mastersizer S) by dispersion of the powder in isopropanol (Cf. Fig. 1). The median particle size of the cement powder is around 11.5 μm . Glass beads with a diameter of 1.5 mm are used as rigid inclusions. The volume fraction of the glass bead is fixed at 50% in the mortar in this study. Two water-to-cement ratios (W/C) are used for the model mortar, i.e. 0.35 and 0.20.

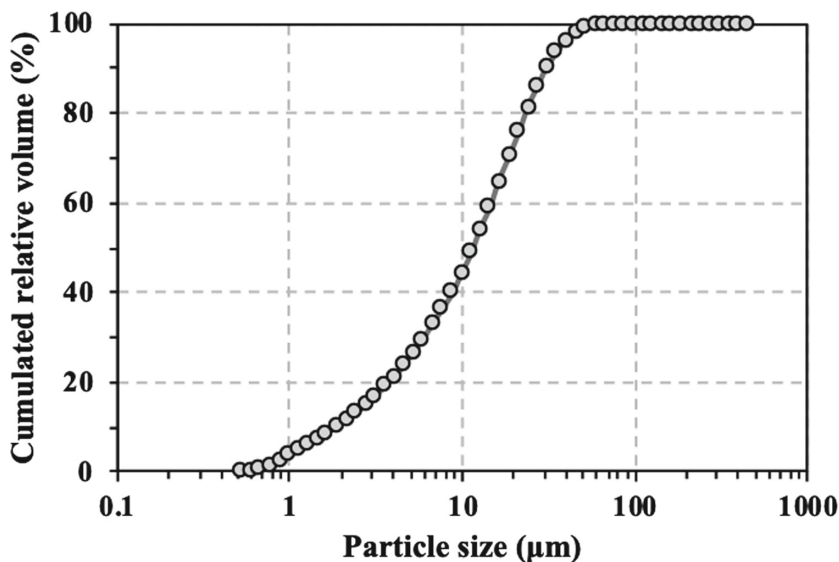


Fig. 1. Cumulative particle size distribution of the cement used in this study.

2.2 X-Ray Computed Tomography (XRCT) Device

The tested mortar is cast into a cuboid mold made by ABS plastic with internal dimension of 50 mm in length, 20 mm in height, and 15 mm in width. The CT images are captured on the XRCT laboratory scanner available at Laboratoire Navier (Ultratom from RX-Solution). It combines a Hamamatsu L10801 source (230 kV, 200 W, smallest spot size: 5 μm) and a Varex Imaging 4343DXV flat-panel imager (3000 $\times$ 3000 pixels, pixel size 139 μm). For each measurement, the scans are performed at 160 kV and 24 μA , with a frame rate of 2 images per seconds. 2336 projections are recorded during the 360° scan. 2 radiographs recorded at the same angular position are averaged. The total scanning time for each specimen is around 15 min. The 3D images of the specimen are then obtained with about 3000 $\times$ 3000 $\times$ 2500 voxels, the voxel size being 18 μm . 3D images have been reconstructed by means of the X-Act software from RX Solutions (Fig. 2).

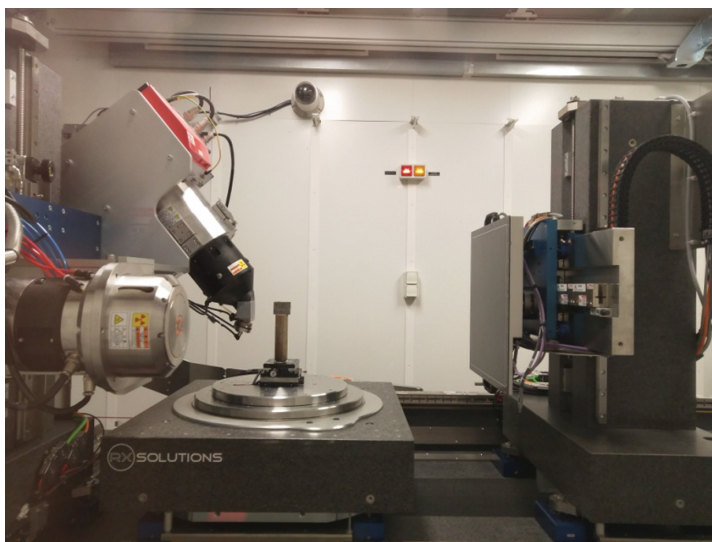


Fig. 2. XRCT device and sample setup.

2.3 Mechanical Strength Measurement

In the current study a 3-point-bending test is conducted to characterize the mechanical strength of the dried and sealed sample which is demolded after the XRCT measurement. The test setup is shown in Fig. 3. A 3D printed ABS plastic mold which is slightly larger than the sample size was used to limit the possible movement of the sample during bending and to precisely apply the bending force. The force is applied vertically to the side surface. Two grooves are reserved in advance at the bottom of the frame with a distance of 40 mm. One groove was reserved at the top center of the frame. 3 iron sticks

are inserted into the grooves to transmit the forces from the compression machine. For all tests, the loading rate is kept constant at 10 N/s. The age of the samples at testing is roughly one month.

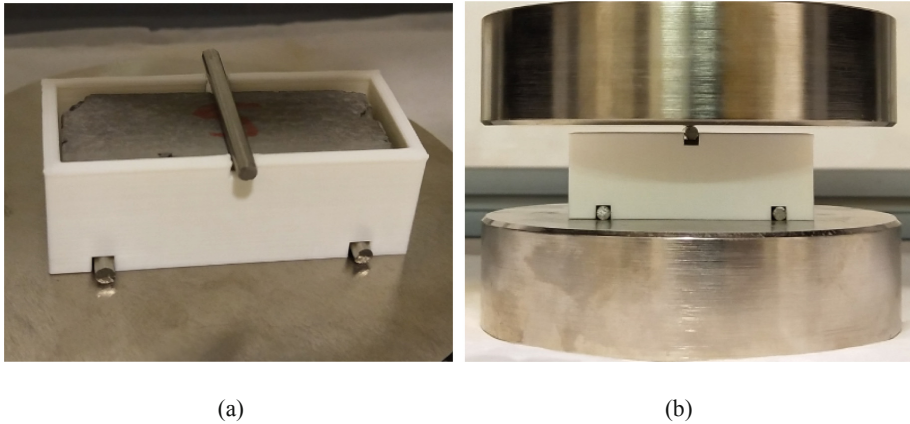


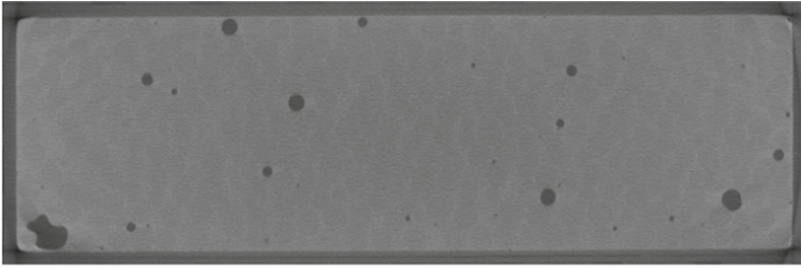
Fig. 3. 3-Point-bending test setup: (a) sample in the mold used for 3-point-bending; (b) under testing.

3 Results and Discussion

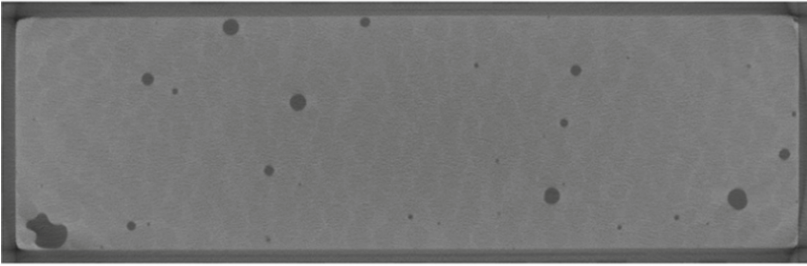
3.1 Influence of Drying Phenomena

We first show in Fig. 4 the horizontal slice (approximately 10 mm from the bottom of the specimen) of the reconstructed samples with W/C of 0.35 for both samples, sealed for 7 h (Fig. 4(b)) and dried for 3 h (Fig. 4(d)) after casting. For the sample subjected to sealing condition (Fig. 4(a) and (b)), besides the cement paste matrix (in light grey color) and glass beads (in dark grey color), only spherical bubbles (in black color) can be observed ranging from several voxels to the size of the glass beads. Apparently with the resolution of the current XRCT scan (18 μm for the voxel), hydration induced microstructural modifications are not detectable. Hence, the microstructure change of the specimen under sealing conditions can be neglected.

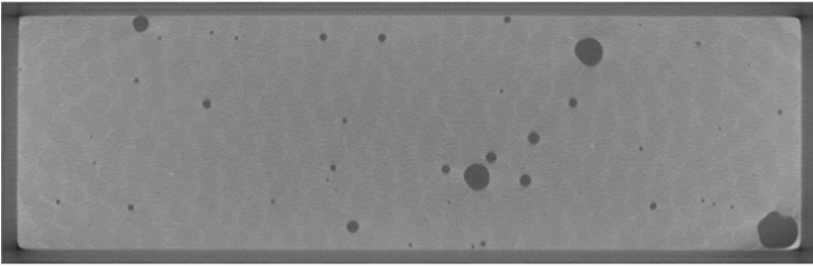
However, for the sample subjected to drying condition, besides the cement paste matrix (in light grey color) and glass beads (in dark grey color), both irregular spherical bubbles and slender twisted cracks (both in dark grey color) are clearly observed compared to the initial state (Fig. 4(c) and (d)). On the one hand, it can be deduced that compared to the regular shaped bubbles for the sealed sample, the irregular shaped bubbles in dried sample are mainly due to the locally inhomogeneous displacement induced extrusion of the glass beads and paste while drying. On the other hand, microcracks with a length of the glass bead size and the width of tens of the pixels (i.e. the order of 100 μm) are observed. This inherent defect at early age of the printed concrete will definitely have an adverse effect on the mechanical properties of the material after hardening.



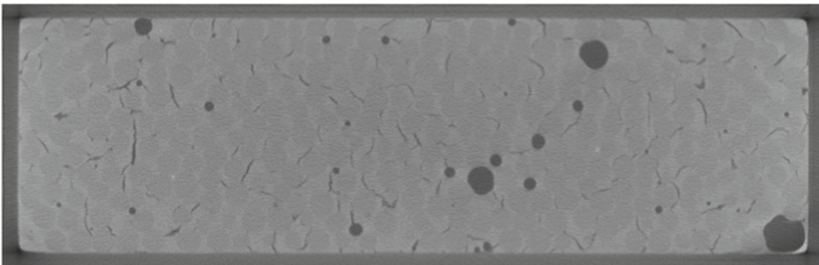
(a)



(b)



(c)



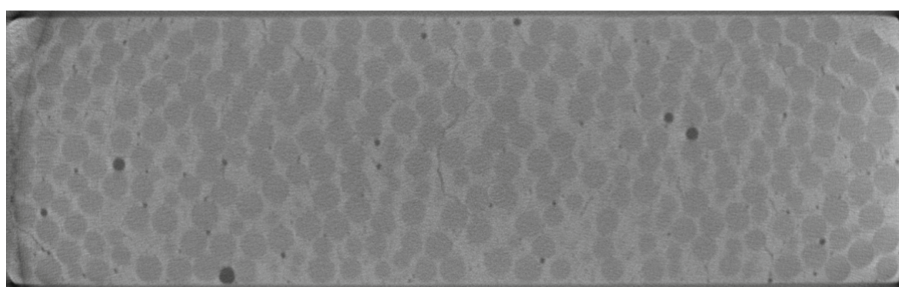
(d)

Fig. 4. Horizontal slice of the reconstructed sample with $W/C = 0.35$: (a) initial microstructure of sample subjected to sealing condition (b) sample sealed for 7 h after casting; (c) initial microstructure of sample subjected to drying condition (d) sample dried at room environment for 3 h after casting.

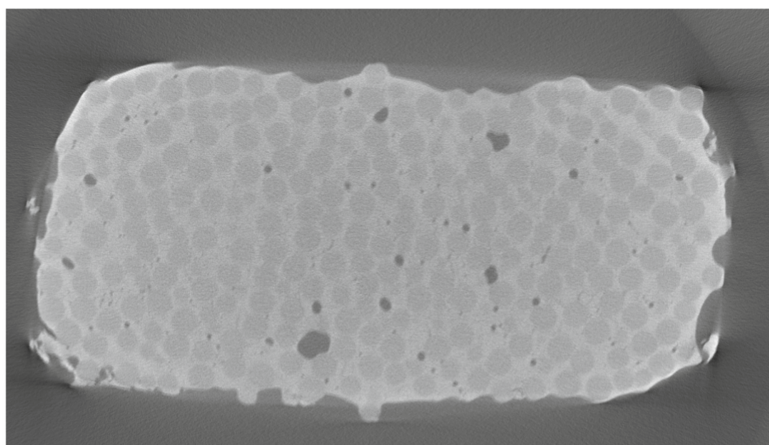
3.2 Influence of Mold

We then show in Fig. 5 the horizontal slice (approximately 10 mm from the bottom of the specimen) of the reconstructed samples with W/C of 0.20 dried for 3 h after casting with mold (Fig. 5(a)) and without mold (Fig. 5(b)). The contrast between cracks and cement matrix are less noticeable, since the mortar is denser than the one with W/C of 0.35 and the X-ray encounters more difficulties to go cross the sample. Anyhow, for both of the samples with or without mold, similarly to the one with W/C = 0.35, slender twisted cracks with the length of the order of the glass bead size can be observed. Moreover, the cracks seem to be narrower than the cracks in the higher W/C mortar.

The above observation suggests that the existence of the mold or the impact of the mold constrains in the current measurement are not the only origin of the microcracks, but the self-constrain of the sample could also lead to cracking under drying conditions.



(a)



(b)

Fig. 5. Horizontal slice of the reconstructed sample with W/C = 0.20 subjected to room drying condition 3 h after casting: (a) sample with mold; (b) sample without mold.

Subsequently, for extrusion-based 3D printing the filaments printed at ambient laboratory conditions will inevitably face the microcracking caused by drying and saturation levels decrease inside of the printed material.

3.3 Mechanical Deterioration Under Drying

In Fig. 6 the loading force is plotted as a function of displacement for the 3-point-bending test for sealed and dried mortar with $W/C = 0.35$. It can be seen from the testing results that both of the samples behave as an elastic brittle material and that they both fail directly after achieving the peak load. Furthermore, the peak force of the dried sample is lower than half of the sealed sample. This means that the microcracks observed in Fig. 4(b) dramatically decrease the mechanical bearing capacity of the material.

We recall here that the drying phenomena during printing of the concrete filament may potentially lead to the microcracking of the concrete which in turn initiates the deterioration of the material in hardened state. Therefore, a well-planned curing strategy should be performed during the printing task which may improve the hardened properties substantially.

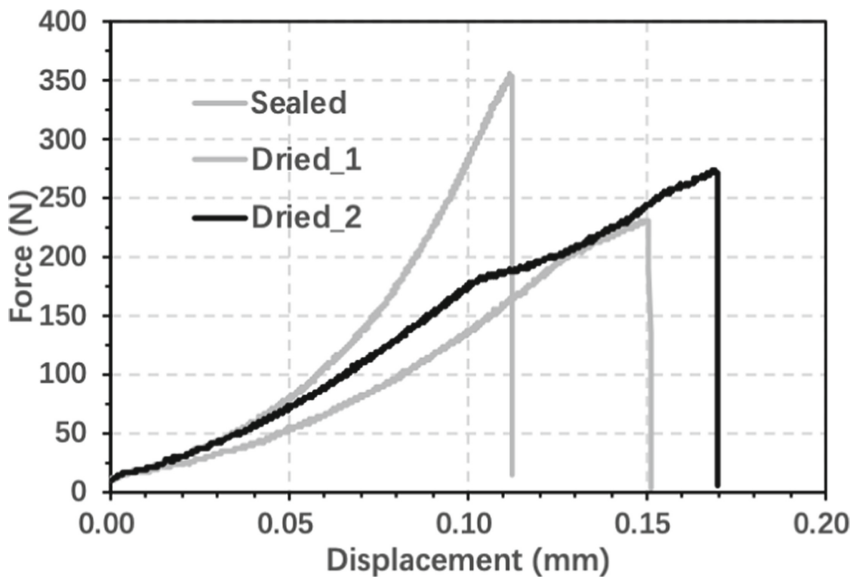


Fig. 6. Loading force as a function of displacement under 3-point-bending test for sealed and dried sample with $W/C = 0.35$.

4 Conclusion and Remarks

In the current study, we have focused on the impact which drying has on the microstructure and on the mechanical strength of one mortar layer. We first compared the 3D tomography of mortar between sealed and dried conditions, and with or without mold constraints at early age. We then carried out the 3-point-bending measurements for sealed and dried mortar. The experimental results suggest that, before setting, drying phenomena induce irreversible microcracks within the structure which can lead to a deterioration of mechanical strength of the 3D printed concrete filaments.

Although we used molds and a manually casting process, the underlying physics of drying does not alter. Therefore, the results obtained in this work can predict the drying phenomenon and its effect on material performance in the actual printing process. Moreover, 3D printed materials may dry faster than our samples due to the higher temperature induced by the accelerated hydration and friction during the printing process [5, 9]. A faster drying rate may cause even more severe microstructure degradations than our observations. Nevertheless, experimental parameters, including extrusion rate, number of layers and diameter of nozzle require further study in order to more closely reflect the impact of the printing process on drying phenomena and material properties.

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Structural engineering & reinforcement



Printed Concrete as Formwork Material: A Preliminary Study

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Abstract. Production of complex formwork with conventional materials can be expensive due to the intensive labor during the manufacturing process. The introduction of printed concrete as formwork material could resolve this problem. The combination of the automated robotic manufacturing and the high degree of freedom could benefit the production process. However, the material characteristics of printed concrete are less suitable than for conventional materials. The low tensile strength of printed concrete formwork could endanger the stability of the formwork during casting of the concrete. This experimental study identifies the most important stresses and parameters to be studied while casting concrete in a printed concrete formwork. The investigation was performed on a printed concrete cylindrical formwork filled with self-compacting concrete. During casting, the strain on the outside of the formwork was measured in time as well as in function of the changing pressure head. Results showed that the strain on the outside of the formwork increased in time, with increasing pressure head.

Keywords: Printed concrete · Self-compacting concrete · Formwork pressure · Hydraulic pressure

1 Introduction

Static formwork is the most common technique used for cast concrete. These formwork elements are mainly made out of rigid materials such as wood, steel or plastics [1]. Although this type of formwork is frequently used for basic elements, the production is quite expensive, making that formwork can be responsible for a large share of the total concrete construction cost [2]. This cost further increases with the formwork's complexity. The use of rigid materials to create curved surfaces increases the labor cost drastically. Next to this, specially shaped forms are mostly used only once, making them economically unfavorable [3]. Therefore, the conventional way of producing static formwork seems inefficient for complex shapes. However, these problems could be overcome by the aid of additive manufacturing, making complex formwork out of printed concrete a plausible option.

The idea to use concrete as a formwork material exists already for a few years. Khoshnevis [4] designed a technique for vertical concrete formwork based on a standard static formwork called: “simple contour crafting formwork system”. The technique is easier in use than conventional static formwork, since only form ties and

layered extruded concrete is used. The advantage of this system is that the new formwork can be constructed with a high degree of freedom. Next to this, no separated formwork materials are needed, which leads to less material waste [5]. However, the material characteristics are less ideal than the production method. The material properties of the concrete sheathing are inferior to the conventional ones, which could be a major disadvantage [4].

The lag of tensile strength of printed concrete and proper reinforcement within the printed material could be a thorny issue. Tensile stresses, which could rupture the formwork, will develop as a result of the interaction between the cast and printed concrete. One of the most critical interactions is the lateral pressure of the cast concrete on the printed formwork during casting [6, 7]. Therefore without knowledge of the cast material, concrete formwork is designed conservative to withstand at least the hydrostatic concrete pressure [8]. In case of printed concrete, the hydraulic pressure is limited by the tensile strength of the formwork as no reinforcement is placed. Therefore, the maximum height of the fresh cast concrete is limited by the printed concrete strength.

The purpose of this study is to identify the most important stresses and parameters to be investigated during casting concrete in a printed concrete formwork. The behavior of the formwork pressure was obtained by using strain gauges [9].

2 Materials and Methods

2.1 Materials

A thick-walled cylindrical formwork was printed with a layer width of 40 mm and a layer height of 15 mm. The inner diameter of the element was set to be 300 mm. The element had a height of 600 mm. The bottom of the element was sealed by plastic foil secured with a fastener as displayed in Fig. 1. Self-compacting concrete was used to fill the core of the element 22 days after printing. The composition of the printed and self-compacting concrete is shown in Table 1.

Table 1. Concrete composition [kg/m³]

Printed concrete		Self-compacting concrete	
CEM I 52.5 N	667	CEM I 52.5 N	360
Sand 0/2 mm	1000	Sand 0/4 mm	853
Limestone filler	287	Limestone filler	240
Water	309	Water	165
Viscosity modifying agent	0.3	Gravel 2/8 mm	263
Accelerator admixture	47	Gravel 8/16 mm	434
Superplasticizer	3.5	Superplasticizer	4.2

2.2 Methods

The density of the self-compacting concrete was measured according to NBN EN 12350-6 (2019) [10], using three cubes ($150 \times 150 \times 150 \text{ mm}^3$).

Several layers were cut of the concrete formwork and 3 prisms ($20 \times 20 \times 110 \text{ mm}^3$) were drilled out of these. The density of the formwork was measured and a three-point-bending test was performed to obtain the flexural strength of the printed concrete. Therefore, the test procedure of NBN EN 1015-11 (2019) [11] was followed with an adjusted span between the rollers (80 mm instead of 100 mm).

The strain on the outside of the printed cylinder was measured by means of strain gauges. Six of these gauges were installed on the element: three at the bottom and three in the middle (height 0.25 m). All three strain gauges were divided along the circumference of the cylinder. The gauges had a length of 20 mm and were glued on the layers to ensure an optimal attachment. SCC was cast in the printed formwork in different layer while strains were measured. The strain on the outer surface of the printed cylinder was measured two times for every 0.1 m layer of concrete height. The first time was immediately after casting the layer and the second measurement was 35–40 s after casting. The temperature was measured by a thermocouple which was attached at the inside of the formwork at a height of 0.25 m. A measurement was performed every 0.1 s.



Fig. 1. Printed cylinder with cast self-compacting concrete

3 Results

3.1 Measurement

Figure 2 shows the strain as a function of the fresh concrete height inside the cylinder. Two sensors (one at the middle and one at the bottom) showed erroneous data. Therefore, the displayed datapoints are the average of two strain gauges. The strain measured at 0 m and 0.25 m are directly proportional to the increase in concrete height. In time, the circumference seems to expand too. During the resting period of 35–40 s, the strain keeps slightly ($0.7\text{--}2.3 \text{ }\mu\text{m/m}$) increasing. The expansion of a concrete layer will lead to a deformation of the surface of the element in the vertical direction. Due to this deformation, a strain is measured of $2.8 \text{ }\mu\text{m/m}$ at middle height when the height of the cast concrete is still below this level.

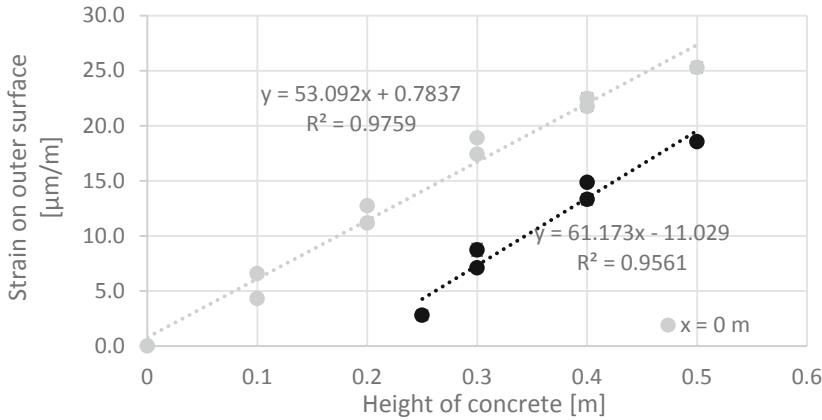


Fig. 2. Strain on outer surface of cylindrical formwork

The strain in function of time is shown in Fig. 3. The start of the casting of the concrete is at timestamp 0 s and a height of 0.5 m is reached after 666 s. The height of 0.25 m is reached after 277 s. As the thermal sensor is placed at this height, it is possible to see that the temperature starts to rise. The temperature of the environment was around 21.9 °C whereas the temperature of the self-compacting concrete amounted to 22.5 °C. As a result, the element was heated up with approximately 0.6 °C.

The resting period held every 0.10 m is not visible in the results. The strain kept increasing in time. The strain measured at the bottom shows a more curved relationship in the beginning, but seems to become linear later in time. In case of the measurement at the middle, the time-strain relation is linear from the moment the SCC reached the level of the strain sensor. The SCC layers from 0–0.25 m were cast at a higher speed than the SCC layers from 0.25–0.50 m. This could explain the steeper increase in strain in the beginning than in the end. After the concrete was cast (after 666 s), the strain kept increasing. The standard deviation for data at the bottom increases until 300 s and varies between 2 and 3 μm/m. The standard deviation on the data measured at the middle is almost nihil (0–0.6 μm/m).

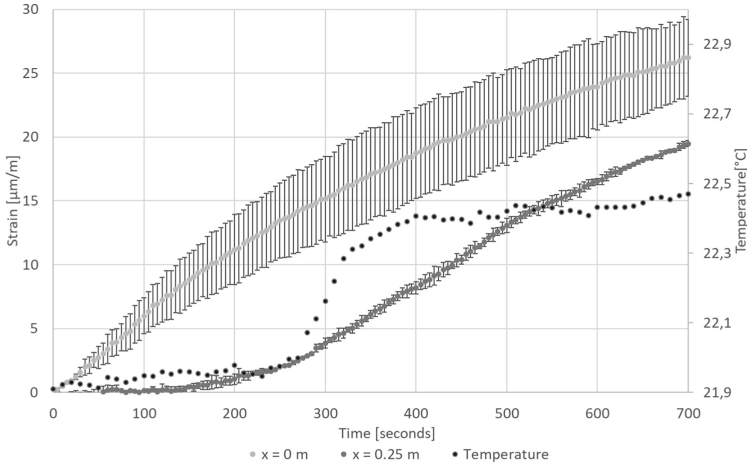


Fig. 3. Strain development during casting concrete

3.2 Calculation

It is assumed that the tangential strain is a result of the combined thermal and mechanical stresses. This assumption is validated by a preliminary and simplified calculation based on the obtained printed formwork and SCC material characteristics given in Table 2 and known equations.

To ease the calculation, only the most critical cross-section of the column is investigated, which is at the bottom of the element. The cross-section is considered to be a solid circular cylinder subjected to a radial temperature variation and inside pressure. In that case, Eq. (1) defines the equilibrium equation for axial symmetry.

$$\frac{d\sigma_{rr}}{dr} + \frac{\sigma_{rr} - \sigma_{\varnothing\varnothing}}{dr} = 0 \quad (1)$$

With r the radius of the cylinder [mm], σ_{rr} the radial stress [N/mm^2] and $\sigma_{\varnothing\varnothing}$ the tangential stress [N/mm^2].

It is most likely that the formwork is subjected to tensile stresses. Feng *et al.* [12] observed that 3D printed specimens may be assumed linear-elastic brittle under tension. Plane strain behavior without creep or cracking of the formwork is assumed, resulting in the stress-strain relation of Eqs. (2), (3) and (4).

$$\varepsilon_{rr} = \frac{1}{E} [\sigma_{rr} - \nu(\sigma_{\varnothing\varnothing} + \sigma_{zz})] + \alpha\theta \quad (2)$$

$$\varepsilon_{\varnothing\varnothing} = \frac{1}{E} [\sigma_{\varnothing\varnothing} - \nu(\sigma_{rr} + \sigma_{zz})] + \alpha\theta \quad (3)$$

$$\sigma_{zz} = \nu(\sigma_{rr} + \sigma_{\varnothing\varnothing}) - E\alpha\theta + G \quad (4)$$

With ε_{rr} radial strain [-], $\varepsilon_{\varnothing\varnothing}$ tangential strain [-], ν the Poisson ratio [0.2], α the thermal expansion coefficient [$10 \mu\text{m/K}$], θ the temperature variation [K], E the modulus of elasticity [N/mm^2], σ_{zz} axial stress [N/mm^2] and G stress due to own weight of the formwork [N/mm^2].

The most obvious cause of the stress in the formwork is due to the lateral formwork pressure. The lateral pressure of the SCC is expected to be equal to the hydrostatic pressure (Sect. 4.3) which can be written as Eq. (5).

$$P = g * h * \rho \quad (5)$$

With P the lateral form pressure [kPa], g the gravitational acceleration [9.81 m/s^2], h the depth of the fresh concrete from the top to the measured point [m] and ρ the cast concrete density [kg/m^3]. This results in a formwork pressure around 11.38 kPa (or 0.011 N/mm^2) for a pressure head of 0.5 m.

By applying the theory of a thick-walled pressure vessel, the tensile hoop and radial stresses on the outside of the element can be calculated. Equations (6) and (7) define the radial stress and tangential stresses at the outside.

$$\sigma_{rr} = 0 \quad (6)$$

$$\sigma_{\varnothing\varnothing} = \frac{2Pa^2}{b^2 - a^2} \quad (7)$$

With P the lateral form pressure [kPa], a the inner radius [m], b the outer radius [m]. This results in a tensile hoop stress of 33.9 kPa.

During the experiment, it was noticed that there is a change in temperature. This temperature rise can lead to an expansion of the concrete formwork. The element is not expected to be fully heated after a few minutes. Therefore, the temperature rise on the outside is likely to be between 0 and 0.6 K (the measured inside temperature rise). The tangential stresses at the outer radius, due to the temperature variation, can be defined as Eq. (8).

$$\sigma_{\varnothing\varnothing} = \frac{E\alpha\theta}{2(1-\nu)\ln\left(\frac{b}{a}\right)} \left[1 - \frac{2a^2}{b^2 - a^2} \ln\left(\frac{b}{a}\right) \right] \quad (8)$$

The tensile hoop stress will vary between 0 and 120.1 kPa, depending on the temperature change.

The strain on the outer surface is calculated by combining the mechanical and thermal stresses together with Eqs. (2), (3) and (4). It is presumed that the modulus of elasticity of the printed element varies around 35000 N/mm^2 . With the varying temperature (0–0.6 °C), the tangential strain is estimated between 1.0 and 11.5 $\mu\text{m/m}$.

Table 2. Element and material characteristics

Parameter	Unity	μ	Std. dev.	COV
Inner diameter	[mm]	263.0	1.5	0.005
Outer diameter	[mm]	340.0	1.5	0.004
Density self-compacting concrete	[kg/m ³]	2320	40	0.017
Density printed concrete formwork	[kg/m ³]	2030	20	0.009
Flexural strength formwork (at 28 days)	[N/mm ²]	5.6	2.1	0.375

3.3 Comparison

The result obtained by the measurement (25.3 $\mu\text{m/m}$) is 2.2–25 times larger than the calculation (1–11.5 $\mu\text{m/m}$). Results in Fig. 2 show that the strain increases drastically with an increasing pressure head. However, in the calculation this effect is rather limited. This could show an underestimation of the effect of the lateral pressure in the prediction. Figure 2 and Fig. 3. both show an increasing strain during the rest periods. However, it is not clear if this is due to the thermal expansion. The large variation in tensile hoop stress and strain are too dependent on the temperature distribution in the formwork, which makes it hard to estimate the influence of this effect.

4 Discussion

In the calculation, thermal and mechanical stresses were assumed to be leading to the tangential strain on the outside of the element. However, the result obtained by the calculation seems to be an underestimation of the observed values. It is likely that the tangential strain is not only a result of the combined thermal and mechanical stresses. Therefore, additional material behavior should be included. However, the underestimation could be a result of an inaccurate estimation of the material properties too. An overview of neglected parameters is given, which could lead to a deviation between the calculated and the observed values.

4.1 Model, Material and Element Properties

The calculation idealizes the experiment as a concrete ring under plane strain, which is isotropic and perfect circular. At the same time, the material properties of the formwork are estimated based on conventional concrete. The values of the Poisson ratio and the linear coefficient of thermal expansion are based on the values in NBN EN 1992-1-1 (2004) [13]. Young's modulus was estimated by using the formulas in this standard [13] and the obtained flexural strength. However, Feng *et al.* [12] showed that printed concrete is orthotropic and that this orthotropy depends of the layer direction. This layered structure reduced the mechanical strength in comparison to conventional concrete. In the calculation, the printed concrete parameters are estimated based on conventional concrete behavior and characteristics, which does not take this layered structure into account. Therefore, the strength and stiffness of the printed formwork are likely to be overestimated.

4.2 Time-Dependent Behavior

Time is not implemented which makes that time-dependent behavior such as creep, shrinkage and hydration are left out. However, this behavior could highly influence the strain rate.

In case of the hydration process, the cast concrete will start generating heat. As a result, the cast concrete will try to expand and induce a pressure on the printed formwork. At the same time a heat flux will lead to an expansion of the printed formwork. In case there is a mismatch in thermal expansion coefficient, elastic modulus and Poisson ratio of the cast and printed concrete, it is likely that a pressure will be generated at the interface. This could lead to tensile stresses in the formwork, which could result in crack formation. In the experiment, only a low temperature increase of the cast concrete is visible. It is assumed that during casting, the generated heat is low and the cast concrete did not expand. Therefore, only the stresses in the printed formwork resulting from the heat flux (due to the temperature difference between cast and printed concrete) are included in the calculation.

Creep is likely to occur for concrete exposed to high sustained load. Bhatnagar *et al.* [14] showed that in case of a thick-walled cylinder subjected to an internal load, the tangential strain increases in time. It is possible that creep occurs. However, the limited measuring time, the small mechanical load and the little knowledge about creep in printed concrete in tension led to the fact that the effect of creep is not assumed in the calculation.

4.3 Reduced Casting Rate

In the calculation a pure hydrostatic pressure is assumed. However, this is probably an overestimation of the real pressure, which results in an overestimation of the strain. Flocculation and the increase of apparent yield stress in the cast concrete lead to a decrease in lateral stress. This is only valid when the concrete is at rest or cast at a low speed from the top. In the experiment, based on the calculation methods proposed in [6], a reduction of 4% and 8% would be possible. However, due to the limited pressure head and the casting time, this reduction was neglected. In case of larger elements, this reduction will have a large impact on the stress control.

5 Conclusions

The purpose of this preliminary study was to detect the most influencing parameters and stresses during casting concrete in a printed concrete formwork, which should be investigated more into detail in further research. The strain development of printed concrete as formwork material was investigated during casting. A cylindrical printed formwork was devolved and the strain was measured during filling with self-compacting concrete.

The measurements indicated that the strain is directly proportional to the height of the cast concrete and further increases in time. Ostensibly, this increment could be related to:

- Lateral pressure. The lateral pressure of the concrete, expected to be hydrostatic, results in only a limited deformation of the element.
- Thermal expansion. The difference in temperature between fresh cast concrete and formwork leads to a heat exchange between the two materials. This results in an expansion of the formwork.
- The formwork rigidity. Due to lateral pressure and expansion of loaded formwork layers, the element will deform in the vertical direction too, which results in an additional strain on the outer surface in unloaded regions.
- Creep and shrinkage. During casting, creep and shrinkage of the formwork material could occur, resulting in a deformation of the elements outer surface.

Based on the obtained results, further detailed research is needed on the formwork behavior and material properties during and after casting of the element to extent and correct the calculation method.

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Bond of Reinforcement Cable in 3D Printed Concrete

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Abstract. The use of high strength steel cables directly entrained into printed concrete during the printing process, has previously been introduced as a method to provide reinforcement to objects being manufactured through a layer-extrusion based 3D concrete printing process. The bond between the cable and the cementitious mortar is a crucial parameter for the structural performance of such reinforcement, and was hence subject of a detailed study presented in this paper. The bond performance was studied in direct and flexural pull-out tests on cast and printed specimens and further analyzed by microscopic analysis of the bond surface. Two effects were identified that significantly decrease the bond strength. Firstly, chemical reactions create a spongy interface of poor strength. Secondly, the flow of mortar around the cable tends to create a cavity underneath the cable which reduces the effective bond surface. Mortar viscosity, nozzle design and filament pressure, were thus identified as important parameters for the bond quality. The average bond quality seems to reduce with embedment length. As a consequence, cable breakage was not achieved, in spite of considerable embedment lengths that were tested. Likely, this was caused by the cumulative probability of critical defects along the increasing embedment length, in combination with a non-constant shear distribution. All test series showed significant scatter. It was concluded that, although this reinforcement method is promising as it can potentially provide sufficient post-cracking strength, the bond quality must be improved considerably both in terms of average strength and reduction of scatter.

Keywords: 3D concrete printing · Reinforcement · Cable · Bond

1 Introduction

New projects based on the structural use of extrusion-based 3D concrete printing (3DCP) are regularly presented [1–10]. A continuing issue with the structural use of 3DCP is the lack of suitable reinforcement methods [11]. In practice projects have used full prestressing [7] or hybrid solutions in combination with cast concrete and conventional reinforcement [5]. In research settings, printable strain hardening cementitious composites (3DP-SHCC) have been presented as an alternative [12], as well as pre- or post-placed reinforcement elements (bars, mesh) [13, 14]. Simultaneous placement of e.g. flexible mesh has also been suggested [15].

In 2017, researchers from the TU Eindhoven introduced a method to entrain a high strength steel wire rope cable into the extrusion filament during concrete printing. A proof-of-concept on beams in bending showed the section resistance could be analyzed analytically similarly to conventional reinforced concrete beams [16]. A subsequent study explored bond properties [17]. The cables were applied in practice for the first time as a supplementary reinforcement in a small bridge [7]. Since its invention, other groups have developed similar systems [18, 19].

The initial studies revealed that the bond strength between the smooth, coated cable and the printed mortar was limited. Particularly the stronger cables used in these studies were thus susceptible to pull-out, rather than cable breakage. This limits the resistance of the cable reinforced section. Therefore, the current study further investigates the cable-mortar bond.

2 Methodology

2.1 Experimental Program

A range of different pull-out tests on cast and printed cable reinforced specimens was performed. In addition, specimens were studied visually as well as with an optical microscope to observe the material structure around the embedded cables. Globally speaking, the research was divided into three phases.

In the first phase, direct pull-out tests on cast specimens with embedded reinforcement cable were performed. The reason to opt for cast rather than printed specimens in this phase was twofold. Firstly, the cast specimens were expected to show the best possible behavior, thus serving as a benchmark for printed specimens. Secondly, cast specimens are easier to make which allows to study some parameters more efficiently. The experiments were supplemented with optical microscopy observations.

The second phase focused on printed specimens and was purely phenomenological in nature. Through visual and optical microscopy observations, the interaction at the nozzle between mortar and cable was studied, as well as the effect of cable position.

Finally, the third phase studied the effects of embedment length in printed cable reinforced beams. Flexural pull-out tests with notched beam specimens were used, rather than direct pull-out specimens. It was verified that the results from these different pull-out tests can be compared.

2.2 Materials and Print Facility

During the research, three different print mortars were used: Weber 3D 115-1, Weber 3D 145-1, and Weber 145-2. The former was initially used by the TU Eindhoven 3DCP research group. A global description of its composition can be found in [20], which also details the print facility that was used for printed all printed specimens. Except for the use of a custom nozzle and the cable entrapment device, default print settings were used.

The group currently mostly uses the Weber 3D 145-2. Wolfs et al. [21] have reported on its hardened state properties. Most of the experiments in this study have

been performed with this mortar. In subsequent sections, it is specified which mortar has been applied in each experiment.

Most experiments were performed with Bekaert Syncrocord Flex 1.2 cable, while in some instances the Bekaert Syncrocord Flex 0.9 has also been used for comparison, with ultimate characteristic tensile strengths of 1925 N and 1190 N, respectively. The global cable perimeters are 3.05 mm and 3.77 mm, but due to their construction from multiple wires, the (theoretical) contact perimeters are 5.11 and 5.87 mm. It is not entirely certain whether the total contact perimeter can actually be activated, but for the calculations of average bond stress, the contact perimeter has been used. More extensive data on both cables can be found in [17].

2.3 Phase 1: Pull-Out of Cast Specimens

For the majority of the specimens, the preparation method and experimental procedure detailed in [17], Sect. 4.1, was applied. A cable was pulled out of a cast block of print mortar, displacement controlled at a speed of 0.5 mm/min. The nominal block dimensions were 100 3 100 3 35 mm³. The embedded cable length corresponded with the mortar block height, i.e. 35 mm (deviations in height of up to +2 mm were measured). Specimen series #1–#5 were cured covered under foil, while series #6 and #7 were cured in water. The experimental series, associated variables, average results, and predicted anchorage lengths are given in Table 1 (results and anchorage lengths are further discussed in Sect. 3). In some cases, the results were supplemented with results from previous tests presented in [17], for comparison. The experimental setup is shown in Fig. 1. Due to effects observed in specimens, the cable orientation during casting was also varied (Fig. 2). This required a slightly different specimen production method, with the concrete cast parallel to the cable.

Table 1. Experimental variables and results of direct pull-out experiment on cast specimens.

Series	Qty.*	Mortar	Cable	Cable orientation during casting	$F_{u,ave}$ [N] (rel. SD)	$f_{b,ave}$ [MPa]	Predicted $l_{anch.}$ [mm]
#1	5	115-1	Flex 0.9	Horizontal	827 (13%)	4.6	51
#2	5 + 5	115-1	Flex 1.2	Horizontal	960 (16%)	4.7	72
#3	5	145-1	Flex 0.9	Horizontal	363 (26%)	2.0	125
#4	5	145-1	Flex 1.2	Horizontal	393 (13%)	1.9	177
#5	5	145-2	Flex 1.2	Horizontal	397 (26%)	1.9	182
#6	5	145-1	Flex 1.2	Horizontal	329 (30%)	1.6	222
#7	5	145-1	Flex 1.2	Vertical	209 (68%)	1.0	442

* numbers in grey indicate experiments from previous research [17].

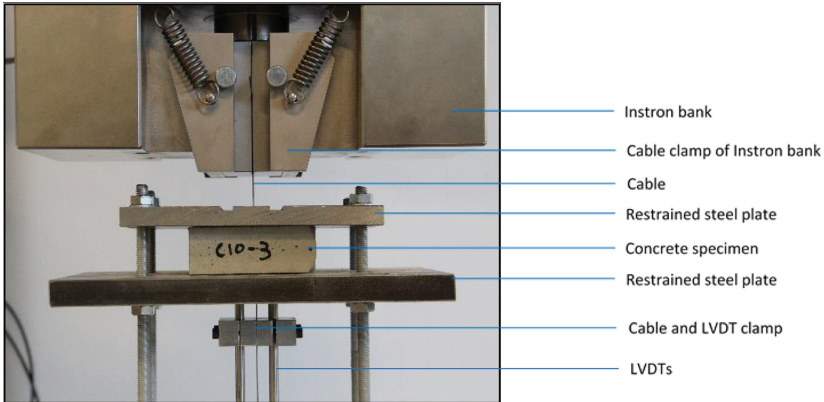


Fig. 1. Test setup for pull-out tests on cast specimens

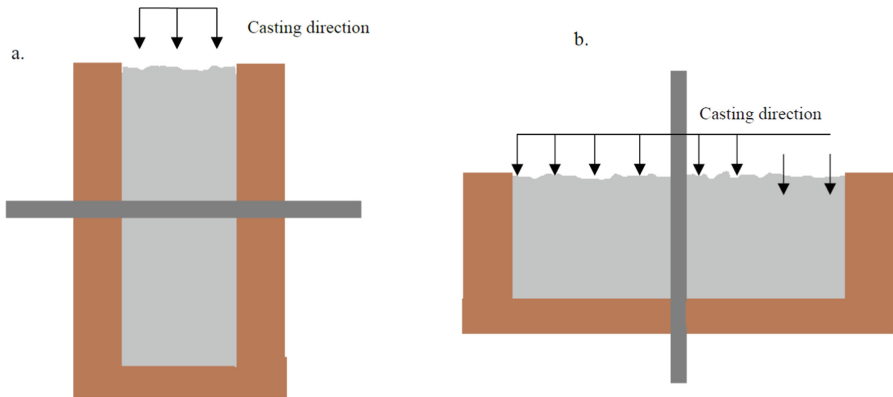


Fig. 2. Cable orientations applied in cast specimens: horizontal, and vertical.

2.4 Phase 3: Flexural Pull-Out and Direct Pull-Out of Printed Specimens

The study on bond in printed specimens has been performed with two types of pull-out tests, a direct pull-out and a flexural pull-out test. The latter method was included as it allows easier specimen preparation with less risk of pre-affecting the cable bond. In addition, it directly provides data on the failure behaviour in a situation of bending, which corresponds with the intended use.

The direct pull-out tests were performed in a similar manner as those on cast specimens. Specimens were obtained from printed straight walls with a height of 5 layers, printed with a back/down flow nozzle (see Sect. 3.2) with a mouth opening of 10360 mm^2 . A reinforcement cable was entrained in the middle layer. Between 1 and 2 h after printing (before the initial set time), the wet concrete was cut and removed between subsequent specimens, to obtain free cable length that could be clamped in the test rig (Fig. 3). This procedure is very time consuming and a major reason to opt for

flexural pull-out tests in subsequent experiments. Specimens with different embedded lengths were prepared, as specified in Tables 2, 3, and 4 for the direct pull-out tests, first and second series of flexural pull-out tests, respectively. These tables also lists experimental results, similar to Table 1. With the exception of one set os specimens tested in direct pull-out, all tests on printed concrete were performed with 145-2 mortar and Flex 1.2 cable.

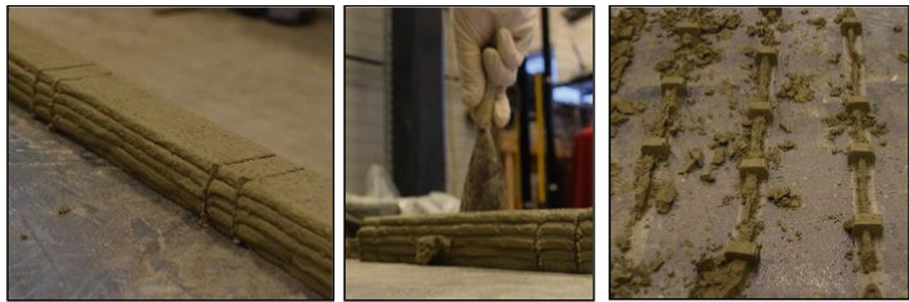


Fig. 3. Illustration of procedure to obtain specimens from printed concrete for direct pull-out tests.

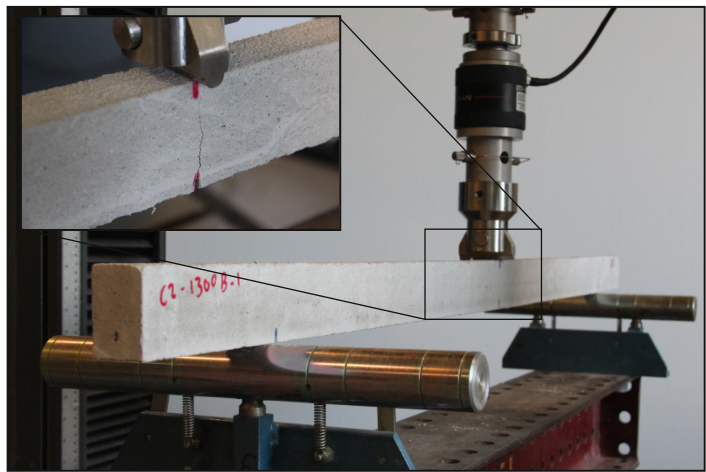


Fig. 4. Flexural pull-out test by 3-point bending on a notched beam (Flex 1.2, 145-2, series 2).

Table 2. Experimental variables and results of direct pull-out experiment on printed specimens.

Qty.*	Mortar	Cable	l_{embed} [mm]	$F_{u,\text{ave}}$ [N] (rel. SD)	$f_{b,\text{ave}}$ [MPa]	Predicted $l_{\text{anch.}}$ [mm]
14	145-1	Flex 0.9	35	282 (53%)	1.58	188
4	145-2	Flex 1.2	35	184 (43%)	1.12	293
8	145-2	Flex 1.2	80	275 (29%)	0.69	476
3	145-2	Flex 1.2	120	266 (6%)	0.38	870
3	145-2	Flex 1.2	160	536 (35%)	0.57	575
3	145-2	Flex 1.2	200	488 (4%)	0.42	788

Table 3. Experimental variables and results of flexural pull-out experiment on printed specimens, series 1 (mortar: 145-2, cable: Flex 1.2). Note that the embedment length is 0.5 times the beam length (not the beam span), and be aware that $F_{u,\text{ave}}$ indicates the pull-out force, not the ultimate load on the cross head in 3-point bending.

Qty.*	l [mm]	l_{embed} [mm]	l_{span} [mm]	$F_{u,\text{ave}}$ [N] (rel. SD)	$f_{b,\text{ave}}$ [MPa]	Predicted $l_{\text{anch.}}$ [mm]
2	120	60	100	362 (26%)	1.03	319
4	160	80	100	277 (14%)	0.59	556
2	200	100	100	361 (4%)	0.61	534
2	240	120	200	460 (10%)	0.65	502
2	280	140	200	391 (4%)	0.48	689
2	320	160	200	336 (46%)	0.36	915
2	360	180	200	608 (20%)	0.58	570
2	400	200	200	666 (11%)	0.57	578
2	440	220	200	706 (7%)	0.55	600
2	480	240	200	979 (26%)	0.69	472
2	520	260	200	1193 (19%)	0.78	419
1	560	280	200	1089 –	0.66	495
2	600	300	200	1025 (5%)	0.58	563

Table 4. Experimental variables and results of flexural pull-out experiment on printed specimens, series 2 (mortar: 145-2, cable: Flex 1.2).

Qty.*	l [mm]	l_{embed} [mm]	l_{span} [mm]	$F_{u,\text{ave}}$ [N] (rel. SD)	$f_{b,\text{ave}}$ [MPa]	Predicted $l_{\text{anch.}}$ [mm]
2	400	200	200	371 (56%)	0.32	1038
2	500	250	200	619 (10%)	0.42	778
2	600	300	500	596 (5%)	0.34	969
2	700	350	500	667 (35%)	0.32	1011
2	800	400	500	615 (16%)	0.26	1253
2	900	450	500	870 (60%)	0.33	996

(continued)

Table 4. (continued)

Qty.*	l [mm]	l_{embed} [mm]	l_{span} [mm]	$F_{u,\text{ave}}$ [N] (rel. SD)	$f_{b,\text{ave}}$ [MPa]	Predicted $l_{\text{anch.}}$ [mm]
2	1000	500	500	1005 (26%)	0.34	958
1	1080	540	1000	881 –	0.28	1180
1	1200	600	1000	1020 –	0.29	1132
1	1300	650	1000	908 –	0.24	1378
1	1400	700	1000	904 –	0.22	1490
2	1500	750	1000	1014 (2%)	0.23	1424
1	1600	800	1000	1018 –	0.22	1512

To further study the cable bond, including in particular the effect of bond length, a flexural test was opted for. Beam specimens of different lengths were printed and subjected to 3 point bending (Fig. 4). The beams of series 1 were obtained from a 7 layer high printed wall, which was sawn to size (40 3 40 mm² section) after hardening. The beams of series 2 were sawn to the same section size, but originated from a 5 layer high wall. All beams were printed with Weber 3D 145-2, and reinforced with one Flex 1.2 cable located in the bottom layer, between 5.5 mm and 9.0 mm from the bottom. At the underside of each beam, in the middle opposite the load point, a 1.0 mm wide and 2.0 mm deep notch was sawn. Upon loading, this results in the controlled occurrence and growth of a perpendicular crack, originating from the notch. From the equilibrium of internal and external moment, Eq. (1), and the test load and setup span, Eq. (2), the cable force and maximum bond force can be calculated easily, Eq. (3), (assuming the bond fails before the cable does).

A disadvantage of this method is that the calculation depends on the internal lever arm z , which cannot be determined exactly unless the constitutive compressive failure behaviour of the concrete is known in high detail. However, in low beam heights as applied here, the possible variation in internal lever arm is rather small, which was considered acceptable when taking into account the difficulties and uncertainties of the alternative pull-out test methods.

$$M_E + M_I = 0 \quad (1)$$

$$M_E = 1/4 F \cdot l \quad (2)$$

$$M_I = N_c \cdot z = N_s \cdot z = N_b \cdot z \quad (3)$$

With: M_E = external moment, M_I = internal moment, F = load in 3-point bending, l = span of 3-point bending test, N_c = normal compression force in the concrete, N_s = normal tension force in the reinforcement, N_b = cable bond force, z = internal lever arm.

3 Results

3.1 Phase 1: Study on Cables in Cast Specimens

Figures 5 and 6 show the results of the direct pull-out tests on cast specimens. The average maximum pull-out forces and corresponding average bond strength, calculated according to Eq. (4), are listed in Table 1. In addition, the predicted anchorage length is given, i.e. the embedded length calculated according to Eq. (5) that would be required to achieve cable breakage rather than pull-out failure, based on the pull-out strength

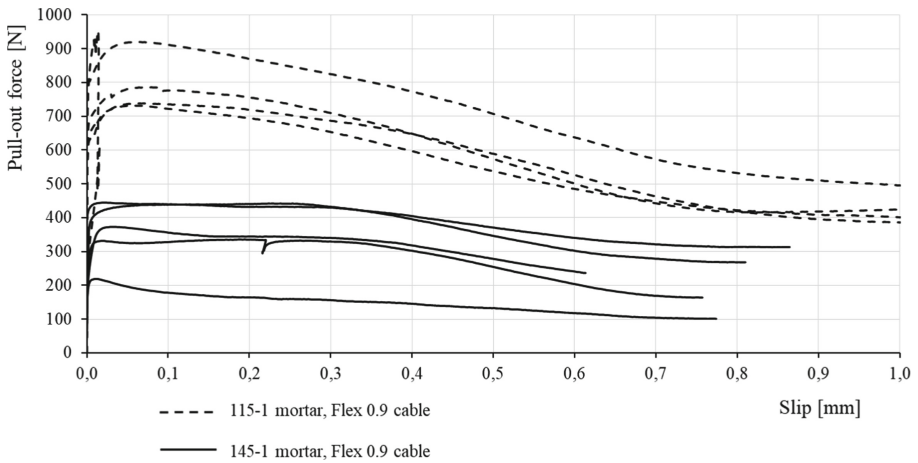


Fig. 5. Load-slip diagrams of direct pull-out tests with Flex 0.9 cable.

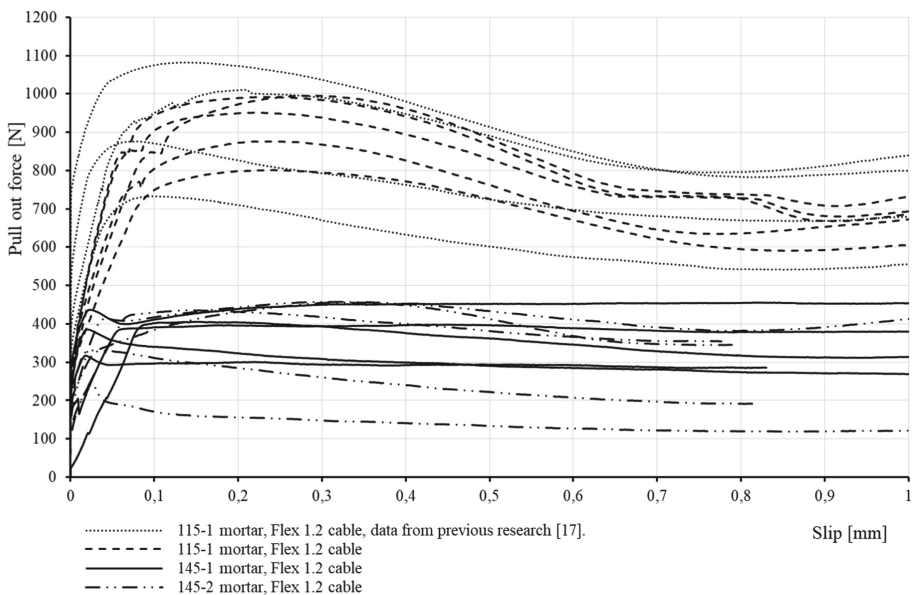


Fig. 6. Load-slip diagrams of direct pull-out tests with Flex 1.2 cable.

and the cable tensile strength. For the calculation of the average bond stress, a constant shear stress along the embedded length was assumed. As will be discussed in Sect. 3.3, this does not correspond to the actual situation. It serves here merely for comparative purposes.

$$N_B = p \cdot l_{embed} \cdot f_{b,ave} \quad (4)$$

With: p = perimeter [mm], l_{embed} = embedded length [mm], $f_{b,ave}$ = average bond strength [MPa].

$$l_{anch.} = l_{embed} \cdot F_{t,cable} / F_{u,ave} \quad (5)$$

With: $l_{anch.}$ = predicted anchorage length [mm], $F_{t,cable}$ = cable tensile strength [N], $F_{u,ave}$ = average experimental pull-out strength [N].

The bond of the Flex 0.9 cable seems to be dominated by adhesion (characterized by the steep initial slope), which, once overcome, is followed by a long gradually decreasing friction resistance. In the specimens with Flex 1.2 cables, the stiff initial adhesion trajectory is followed by a decidedly more compliant behavior up to the maximum resistance. Since the maximum resistance is not much higher and a significant difference in dilatancy is thus not obvious, it seems this may be caused by the difference in the wire rope cable structure, which in the Flex 1.2 cable may allow more sliding of wires along each other. For an application as reinforcement, this could be beneficial as it allows for a higher deformation capacity.

Perhaps the most striking result, is the difference in maximum pull-out load and bond stress that is obtained in the 115-1 mortar versus the 145-1/-2 mortars. Whereas the 145-1/-2 mortars have a significantly higher tensile and compressive strength than the 115-1, the bond strength is more than 50% lower. Considering that the bond strength of conventional reinforcement in normal cast concrete is assumed to increase (linearly) with the concrete (tensile) strength, this result is counter intuitive. However, in conventional cast concrete, the pull-out resistance is mainly generated by dilatancy caused by the ribs or indentations on the bars. For the cables with their smooth surface, on the other hand, adhesion is the dominant bond mechanism. This is primarily determined by the chemical interaction between the cable (surface) and the mortar. The 145-1/-2 mortars apparently contain constituents (e.g. additives) that interact negatively with the cable surface.

Specimens were studied visually and subjected to optical microscopy to further study the bond behaviour. When comparing 115-1 and 145-1 specimens which had been cut open and the cable removed, it was found that the contact surface area of the 145-1 specimens less distinctively showed the cable surface imprint (Fig. 7). Rather, a spongy like interface was found (Fig. 8). This could be attributed to hydrogen formation, a known reaction between galvanized reinforcement and cementitious mortars

[22]. However, since the interface material nor the matrix or the cable surface was studied with regard to its chemical composition, it could also be the product of another chemical reaction. In any case, it is assumed this interface is relatively soft and therefore reduces the bond strength.

The visual study also showed that small horizontal cracks had appeared in about half of the specimens with mortars 145-1 and 145-2, at a small distance below the cable. These cracks did not occur in the specimens with the 115-1 mortar. Neither (and contrary to expectation) could they be clearly correlated to the pull-out strength. The cracks might be attributed to local segregation around the cable, resulting in areas with a higher degree of additives underneath the cable, while larger aggregates are collected above the cable. To avoid this, an additional series of specimens was prepared in which the cable was orientated vertically, i.e. parallel to the casting direction (Fig. 2). The pull-out results of this series are also given in Table 1. Indeed, these specimens did not show cracks around the cable, thus supporting the assumption regarding their cause. However, their average pull-out resistance was much lower, and the coefficient of variation much higher. This leads us to suppose that the self-weight of the mortar pressing on the cable (as in the specimens with horizontally orientated cables) has a significant beneficial effect on the bond.

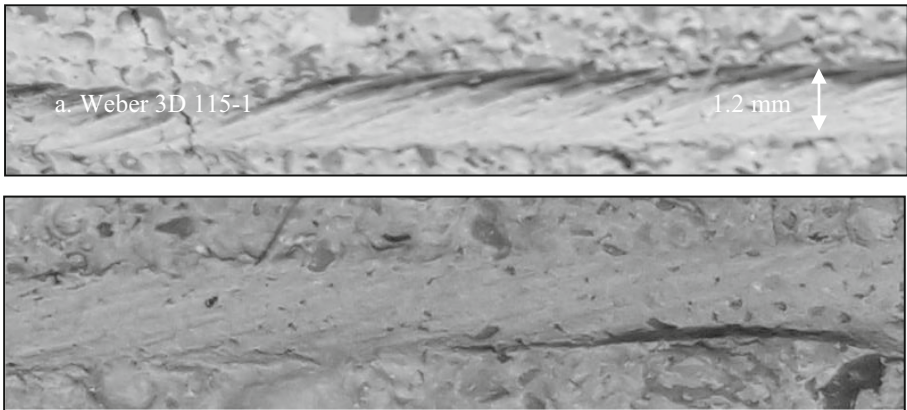


Fig. 7. Specimens with Flex 1.2 cable, after cable removal. The top specimen, with 115-1 mortar, shows a much more clear cable imprint than the bottom specimen, with 145-1 mortar.

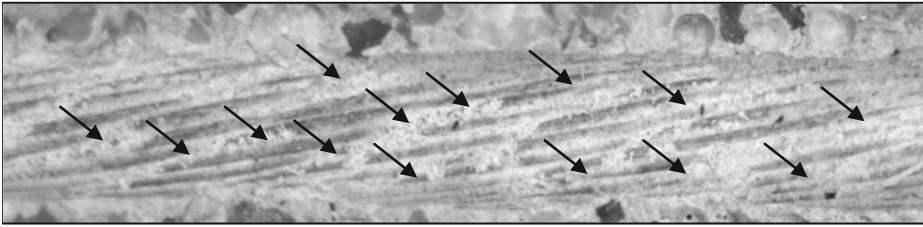


Fig. 8. Spongy like interface (indicated with arrows), observed in a specimen of mortar 145-1.

3.2 Phase 2: Non-destructive Study on Cable Introduction

Several parameters associated with the cable introduction in printing and their effect on bond were optically studied, using the Flex 1.2 cable and different types of mortar. Globally, it was found that the concrete flow coming from above is 'cut' by the cable that is introduced horizontally (Fig. 9). It subsequently needs to flow around the cable. This has two effects. First of all, a cavity can remain underneath the cable, while secondly segregation of constituents may occur, as larger aggregates are blocked by the cable, while smaller ones flow around it.

Both effects have been observed visually and with optical microscope (the cavities are illustrated by Fig. 10). The extent to which this happens depends on a number of parameters, including:

- the mortar (contrary to expectation, more severe cavities occurred in the 145-2 mortar, than in the 115-1 mortar which has a higher initial strength and stiffness [23]),
- the height of the entry point of the cable (the lower the entry point, the smaller the cavity, see Fig. 10), and

Probably, the angle between the flow direction of the filament and the entry of the cable plays a role too, but this was not studied. Actually, neither of these effects was studied extensively, and should be subject of further research.

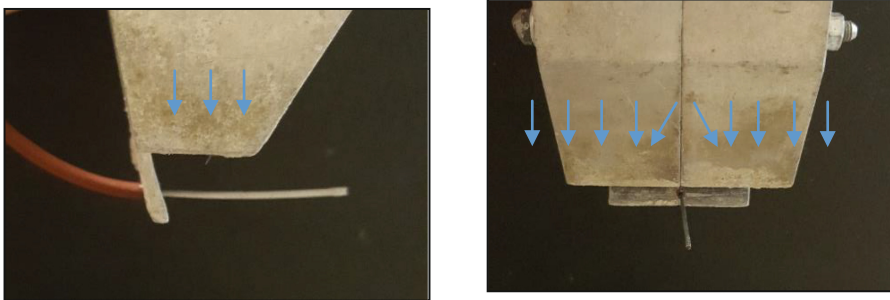


Fig. 9. Interaction between flow of filament and introduction of cable. The cable forces the filament to flow around out, effectively 'cutting' the filament in two.

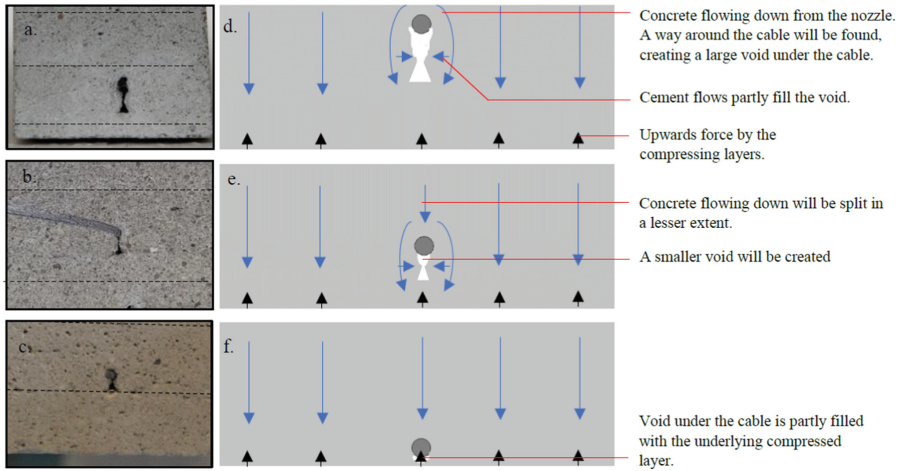


Fig. 10. Cables implemented at different heights in the nozzle (a, bottom, b, middle, c, top) of the printed layer. Layers are indicated with dashed lines. Analysis are visualized in the sketched cross section of a printed layer (d–f).

3.3 Phase 3: Study on Cables in Printed Specimens

Two experiments were carried out: direct pull-out tests, and flexural pull-out tests. The flexural pull-out specimens were performed on two series of specimens. The direct pull-out tests and the first series of flexural tests covered embedment lengths from below until over the theoretical anchorage length as calculated from the pull-out tests on cast specimens (Table 1). Hence, it was expected cable breakage would occur at some point. However, as this in fact did not occur, a second series of flexural pull-out tests was performed on specimens with much larger embedment lengths. Figures 11 and 12 represent the results, in terms of maximum pull-out force, and maximum average bond stress, respectively. Tables 3 and 4 also list the (average) results.

First of all, when comparing the results of the Flex 1.2 direct pull-out and flexural pull-out tests (series 1), it may be concluded that the results are in the same range. The flexural pull-out test thus seems to be an acceptable alternative to the direct pull-out test. Secondly, the scatter in test results is striking. In cases, a factor 2 difference or more was found between test results. This makes it difficult to interpret the experimental results and to identify trends. Also, when considering application of this reinforcement method in practice, this would have a tremendous impact on applicable design values of bond strength. They would be much lower than the average strength obtained from experimental testing. This reinforcement method requires further development to reduce this scatter, if only for this reason.

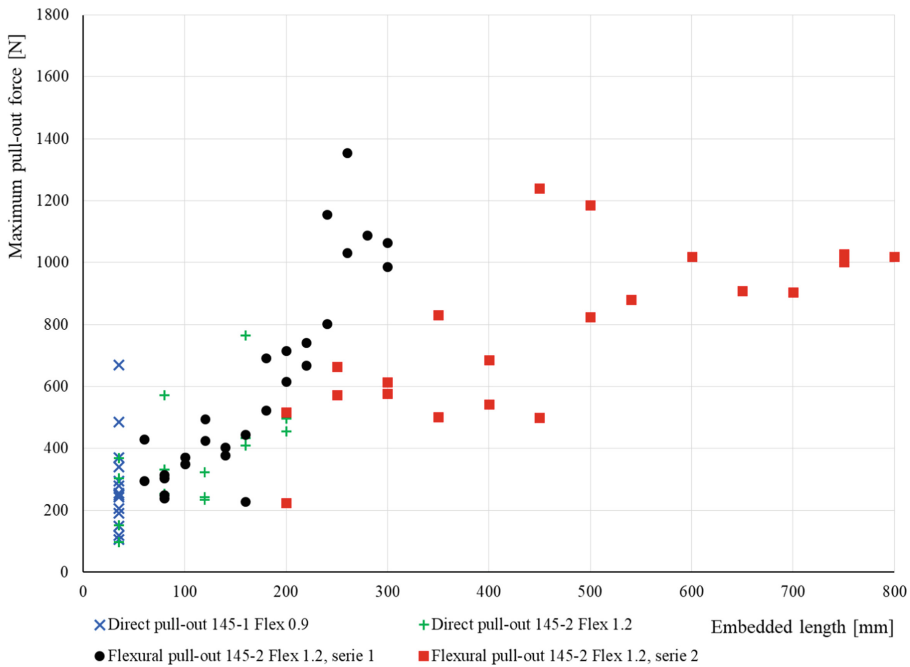


Fig. 11. Embedment lengths versus maximum pull-out loads, experimentally obtained from direct pull-out tests and two series of flexural pull-out tests on notched beams (individual results).

The recorded strengths for the 35 mm embedded direct pull-out specimens are considerably lower for printed concrete than for cast concrete (cf. series #4, #5, #6 in Table 1, and the first two rows in Table 2). However, the difference is smaller than values reported in [17].

Of the flexural pull-out tests, series 2 showed significantly lower pull-out resistance than series 1 (cf. results for 200, 250, and 300 mm embedded length). There is no clear cause for this difference. The number of stacked layers (7 in series 1, versus 5 in series 2) might have played a role, but it would be surprising if this would yield so large variations. Small deviations in the cable introduction at the nozzle may also have contributed.

Perhaps the most remarkable result is that in none of the specimens, cable breakage occurred, regardless of the embedment length. Based on the direct pull-out tests on cast specimens with horizontally orientated cables during casting, cable breakage should be expected to occur at an embedment length of approximately 200 mm or more. However, the average maximum bond strength found in all series of printed specimens was lower than in the cast specimens, but also seemed to significantly decrease further for longer embedment lengths (Fig. 12; although it is not possible to deduct this with certainty due to the small number of specimens and large scatter). Therefore, based on the direct pull-out tests and the flexural tests series 1, the predicted anchorage length ranged from around 300 to 900 mm. As the average bond strength of the flexural series 2 was even lower, this series predicted embedment lengths for cable breakage of approximately 750 to 1500 mm (Tables 3 and 4).

The strength difference between cast and printed specimens could be explained from the lack of compaction specimens and (possibly even more important) the cavity that occurs beneath the cable in printed specimens. However, this does not necessarily explain the reduction in average bond strength at increasing embedment lengths. It is suggested there are two main causes for this phenomenon. On the one hand, it should be noted that the bond stress distribution is not constant along the bond length. Different stress distribution models have been proposed [24–26], but they have in common that a maximum occurs at a certain point that reduces to 0 over finite bond length. Hence, there is a maximum bond force that from a certain embedment length does not increase further. Considering that cable-mortar bond is generally quite weak in printed specimens, it is conceivable that the cable strength just cannot be reached.

Another cause, that is possibly even more relevant, is the cumulative probability of crucial defects along the bond length. The experiments on 35 mm embedment lengths show significant scatter. Thus, in many cases defects are decreasing the potential maximum strength. Over a long embedment length it becomes increasingly likely such defects occur and acts as a weakest link from which debonding may start. In the applied flexural pull-out tests, this effect is amplified by the fact that the experiment always records the strength of the weaker of the two bonded ends on each side of the crack.

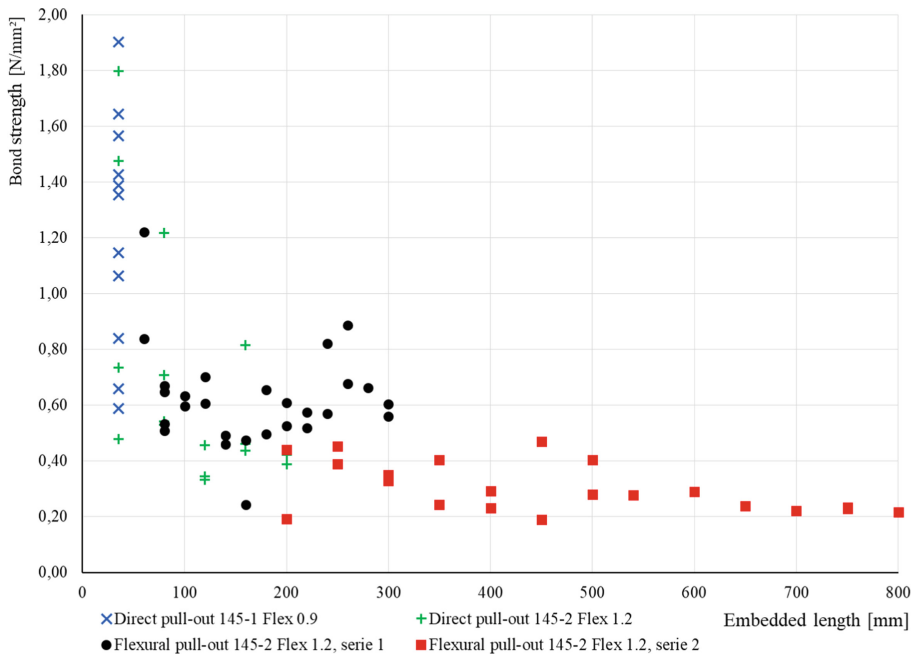


Fig. 12. Embedment lengths versus average bond strength.

4 Conclusions

The bond quality and strength of reinforcement cables entrained in 3D printable mortar were studied experimentally with pull-out tests, and supplemented with visual and microscopy observations. It was found that chemical interaction between the mortar and cable may deteriorate the bond quality. Furthermore, the bond strength in printed specimens with cable reinforcement is generally lower compared to cast specimens. This is likely caused by the lack of compaction as well as the flowing of the mortar around the cable, which creates a cavity underneath the cable.

Importantly, the bond strength seems to reduce further with increasing embedded length. It is suggested that this is caused by a non-constant bond stress distribution and the cumulative probability of bond defects. As a result, cable breakage could not be achieved, which significantly limits the maximum (moment) resistance of a section.

The results render it imperative to improve the bond quality in extrusion-based 3D printed concrete reinforced with automatically entrained cable. The authors intend to allocate future research efforts at this.

Acknowledgements. The support of the staff of the Structures Laboratory Eindhoven and the assistance in the 3DCP research of Master track students Structural Design is gratefully acknowledged. This publication is based on the MSc graduation thesis of the second author, which can be found in the repository of the TU/e library: https://research.tue.nl/files/108239448/Dezaire_0810235.pdf. It is part of the TU/e Impulse II project ‘3D printing of sustainable concrete structures’, which is co-funded by a partner group of enterprises and associations, that consisted of (alphabetical order) Ballast Nedam, BAM Infraconsult bv, Bekaert NV, Concrete Valley, CRH, Cybe, Saint-Gobain Weber Beamix, SGS Intron, SKKB, Van Wijnen, Verhoeven Timmerfabriek, and Witteveen+Bos. In this particular study, materials supplied by Bekaert NV and Saint-Gobain Weber Beamix were used. All support is gratefully acknowledged.

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Experimental Investigation of Topology-Optimized Deep Reinforced Concrete Beams with Reduced Concrete Volume

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Abstract. This paper presents an experimental investigation of digitally manufactured, reinforced concrete beams designed with topology optimization. The backbone of the current work is a hybrid mesh topology optimization algorithm that automatically generates strut-and-tie layouts. The resulting designs have tensile truss elements describing the reinforcing phase and compressive continuum force flow elements that illustrates how the concrete is carrying load. The aim of this work is to investigate the effect of removing a percentage of the non-load carrying concrete phase. A beam is designed with a standard, by-hand approach and the same steel amount is used in to generate a topology-optimized design. This work considers three beam designs; (i) the standard, (ii) a topology-optimized beam with a prismatic section (i.e. 100% concrete), and (iii) the topology-optimized steel layout in a beam with a reduced concrete volume (herein 75%). An alternative reinforcement method is used in which steel plates are cut by waterjet. To improve the bond quality between concrete and reinforcement, corrugations and anchors are added to the steel layouts. However, as opposed to previous experimental tests conducted by the authors, a poor bond quality is achieved, leading to premature failures of all test specimens. Due to the lack of proper bonding, comparison can only be made in the early elastic range. Here, a significant trend is that the by-hand and the topology-optimized specimens with 75% concrete exhibit near identical behaviors.

Keywords: Topology optimization · Generative design · Waterjet cut reinforcement · Experimental testing

1 Introduction

With the recent rapid development of digital manufacturing technologies there is a growing need for design methods that fit the new fabrication and construction paradigm. Topology optimization offers a means to leverage the new possibilities since it is free-form generative design approach that does not require the designer to have a preconceived notion of the final layout of the design. It only requires the

definition of a design domain with applied loads and boundary conditions, and will seek to efficiently distribute material within this domain. The design problem is formulated as a formal optimization problem and most rigorously solved using a mathematical program. Topology optimization has been known to lead to new, often complex and surprising solutions that typically outperform conventional low weight designs [1]. Since concrete has an initial liquid, highly formable state, digitally manufactured topology-optimized reinforced concrete (RC) structures have the potential to save material, while maintaining the performance level of conventional designs.

Several topology optimization algorithms have been suggested for improved design of RC structures. Efforts have e.g. focused on automatically designing layouts for strut-and-tie models [2,3], designing pre-stressed RC [4] or including stress-constraints [5]. However, there exists few literature examples on topology-optimized RC structures that have been built and even fewer examples of experimental testing and validation of the designs. Exceptions include Dombernowsky and Søndergaard [6] that constructed a RC frame designed with a commercial software and Jipa et al. [7] that fabricated two floor slabs of fiber-reinforced ultra-high performance concrete. Recent work by the authors designed, digitally constructed and experimentally tested topology-optimized plain concrete beams [8] and RC beams [9]. In the latter, the reinforcement layout was designed using the bilinear hybrid mesh topology optimization algorithm from Gaynor et al. [3] and test specimens were constructed by waterjet cutting the reinforcement layout from steel plates. These were inserted into prismatic beams. Hand designed beam specimens were thus compared to topology-optimized beams that had the same amounts of both concrete and steel. A 20+% improvement of both stiffness and strength was observed.

This work seeks to design low-weight RC structures that maintain the behavior of conventional RC design. The backbone is an extension of the bilinear hybrid mesh topology optimization algorithm from Gaynor et al. [3]. The algorithm was originally developed to generate strut-and-tie models for deep beams and uses a hybrid truss-continuum mesh. It is set up so that all the force flow in compression is visualized by the continuum elements whereas the tensile forces are guided to the truss elements. The resulting designs provides the steel layouts, ready for sizing, and the beams are intended to be prismatic and have a standard 100% concrete volume. However, the computational design results have regions with zero force flow. This work seeks to experimentally investigate the effects of excluding zero-force regions from the physical designs.

Three deep RC beam designs are experimentally evaluated; (i) a standard design, (ii) a topology-optimized with 100% concrete, and (iii) a topology-optimized design with a reduced concrete volume. All tested beams have the same amount of steel, two will have 100% concrete ((i) and (ii)) and one ((iii)) has a reduced concrete volume. Herein, the reduced concrete volume is chosen to be 75% concrete as it is stipulated that a 25% reduction will not cause problems related to lack of development length.

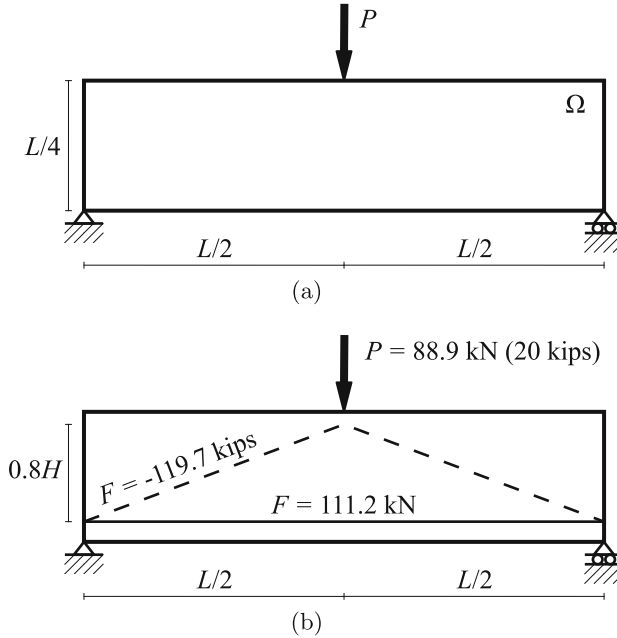


Fig. 1. (a) Simply supported beam design case used herein, and (b) standard strut-and-tie hand calculated design.

1.1 Standard Strut-and-Tie Design

In this work, a simply supported beam design case is considered. The design domain Ω and applied loads and boundary conditions are shown in Fig. 1a. Due to size restrictions of the available testing equipment, the following dimensions are used: $L = 91.4 \text{ cm (36")}$ and $H = 22.9 \text{ cm (9")}$. The thickness of the beam is taken as $t = 5.1 \text{ cm (2")}$ and the design load is chosen as $P = 88.9 \text{ kN (20 kips)}$.

An initial standard strut-and-tie design is conducted following the ACI 318 [10] guidelines to obtain a control steel volume. A simple strut-and-tie layout is chosen and the forces in all members are found as shown in Fig. 1b. The bottom steel bar is then sized accordingly, resulting in a total steel volume of $V_t = 365.8 \text{ cm}^3 (22.32 \text{ in}^3)$.

1.2 Topology-Optimized Design

A full review of the original algorithm by Gaynor et al. is beyond the scope of this paper and the reader is referred to [3] for further details. However, in the current work, all beam designs are desired to have the same steel volume. Therefore the topology-optimized design herein is obtained using a slightly modified formulation. The change of formulation ensures that both concrete and steel

volumes can be constrained and is defined as follows:

$$\begin{aligned}
& \underset{\phi, \rho_t}{\text{minimize}} && f(\rho_c, \rho_t, \sigma_c, \sigma_t) = \mathbf{F}^T \mathbf{d} \\
& \text{subject to} && \mathbf{K}(\rho_c, \rho_t, \sigma_c, \sigma_t) \mathbf{d} - \mathbf{F} = \mathbf{0} \\
& && c_c(\rho_c) = \sum_{e \in \Omega_c} \rho_c^e v_c^e - V_c \leq 0 \\
& && c_t(\rho_t) = \sum_{e \in \Omega_t} \rho_t^e v_t^e - V_t \leq 0 \\
& && \phi_{\min} \leq \phi_i \leq \phi_{\max} \quad \forall i \in \Omega_c \\
& && 0 \leq \rho_t^e \quad \forall e \in \Omega_t.
\end{aligned} \tag{1}$$

Here, ϕ_i are the design variables that control the continuum (concrete) element densities. The design variables are continuous and bounded by $\phi_{\min}$ and $\phi_{\max}$ that in this work are taken as 0 and 1. The volume constraints $c_p(\rho)$ are calculated as the sum of the element density ρ_p^e times the element volume v_p^e over all elements e of the considered type ($p = c$ for continuum elements and $p = t$ for truss elements). The allowable amounts of material are the user specified values V_p that herein are taken as $V_t = 365.8 \text{ cm}^3$ (22.32 in^3) and $V_c = 75\%(L \cdot H \cdot t)$. Throughout the optimization the structure must fulfill the discretized stress-dependent static equilibrium where $\mathbf{K}(\rho_c, \rho_t, \sigma_c, \sigma_t)$ is the global stiffness matrix, $\mathbf{F}$ is the global load vector and $\mathbf{d}$ contains the free displacements.

The truss elements are arranged in a ground structure and allowed to have variable size. The ground structure is placed such that a cover layer is present on the top and bottom of the design domain. For the continuum elements, this work uses the Heaviside projection method [11] as the filtering approach and the Solid Isotropic Material with Penalization (SIMP) [12] method is used to penalize the stiffness of intermediate densities.

In the current work, the Young's moduli of steel and concrete have been taken as $E_c = 25 \text{ GPa}$ (3600 ksi) and $E_s = 200 \text{ GPa}$ (29,000 ksi), respectively. The Poisson's ratio of the concrete is assumed to be $\nu_c = 0.20$.

In Fig. 2a the initial design is shown, where the intermediate density concrete elements are grey and the truss elements in the red ground structure are sized equally. Figure 2b gives the final design obtained by solving Eq. (1) with the Method of Moving Asymptotes (MMA) [13] as the gradient-based optimizer. The final design is seen to have a clear black and white description of the force flow in the concrete. Additionally, the reinforcing bars have been sized and reveals a layout with several different sizes in the bottom region of the beam.

2 Digital Fabrication

Three beam types are digitally fabricated, experimentally tested and compared; (i) the standard strut-and-tie design, (ii) the topology-optimized design with prismatic concrete (100% concrete), and (iii) the topology-optimized design with

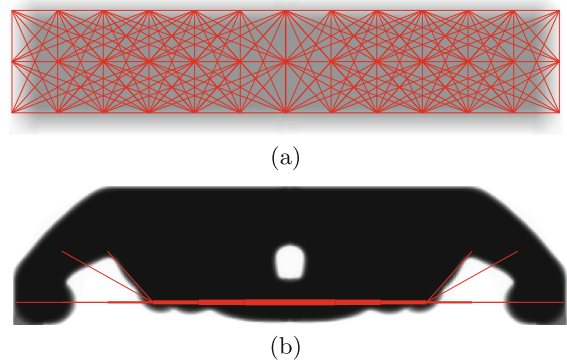


Fig. 2. (a) Initial and (b) final topology-optimized beam designs.

reduced concrete volume (75% concrete). The three designs are shown in Fig. 3 where the white volumes show the concrete phases and the hatched regions indicates where reinforcement is placed. Two test specimens are made of each design.

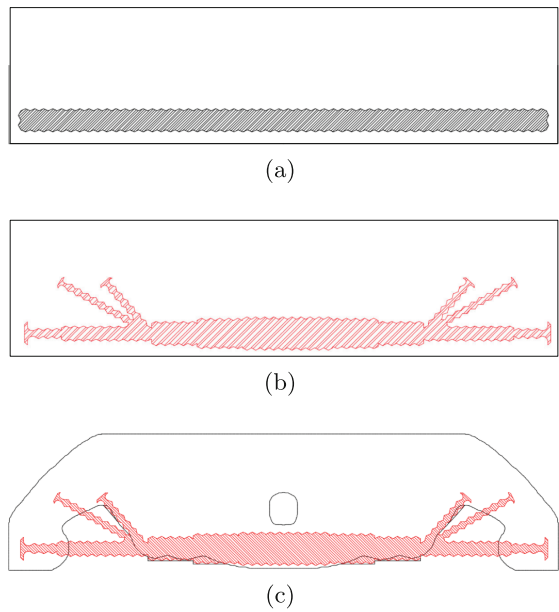


Fig. 3. Experimentally tested designs; (a) standard strut-and-tie design, (b) topology-optimized design with prismatic concrete (100% concrete), and (c) topology-optimized design with reduced concrete volume (75% concrete)

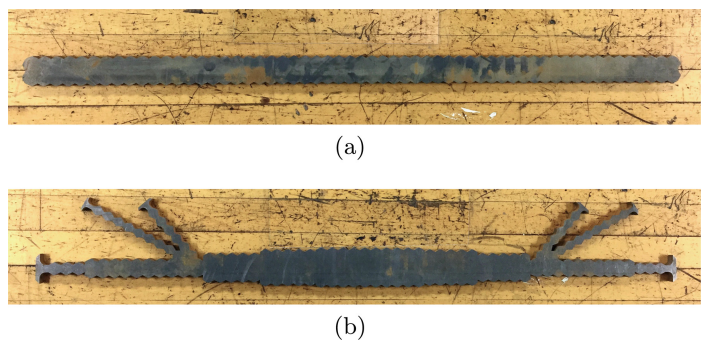


Fig. 4. Examples of waterjet cut steel reinforcement used in beam specimens with (a) standard strut-and-tie design, and (b) topology-optimized designs with both 100% and 75% concrete volumes.

The steel reinforcement is manufactured by sending the digital reinforcement designs to a OMAX CNC-controlled waterjet cutting machine. In this work, the reinforcement is cut from 1.3 cm (0.5”) thick steel plates. To improve the bond between concrete and reinforcement, corrugations and anchors are added to the digital layouts. Triangular corrugations are applied to all straight edges and the anchors used in [9] are placed at free ends of the topology-optimized specimens. Figure 4 shows examples of the fabricated reinforcement.

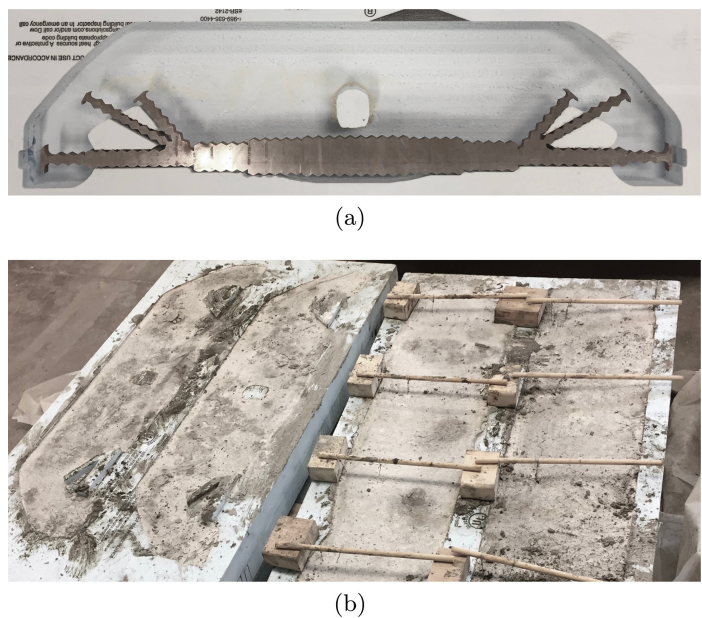


Fig. 5. Concrete casting process where (a) shows a styrofoam mold used for fabrication of a topology-optimized specimen with 75% concrete, and (b) shows the concrete filled molds.

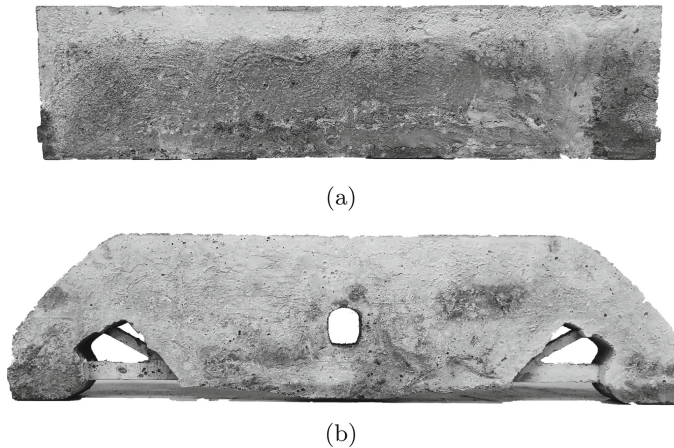


Fig. 6. Examples of digitally fabricated test specimens where (a) is a topology-optimized beam with 100% concrete volume, and (b) is a topology-optimized beam with 75% concrete volume.

The concrete molds are digitally manufactured by CNC milling of styrofoam with an ONSRUD 3-axis mill. The molds are subsequently generously lined with petroleum jelly. A concrete mix is designed with a compressive strength of 27.6 MPa (4 ksi) and poured into the molds. To limit imperfections caused by reinforcement placement, the steel layouts are hanged using wires and wooden dowels. Figure 5 gives an example of a styrofoam mold and shows the casting process.

All test specimens are demolded after two days and placed in a wet environment to hydrate for another 26 days prior to testing. In Fig. 6 examples of the fabricated test specimens are shown.

3 Experimental Results

All specimens are experimentally tested on a Baldwin Universal Testing Machine (UTM). Concrete cylinder tests are first performed to evaluate the quality of the cast concrete. The compressive strengths are found to be reasonably close to the assumed 27.6 MPa (4 ksi) with a variation of -1.8 – 3% .

For the beam tests, a simulated pin and roller is placed at each end of the considered specimen and a point load is applied at mid-span using displacement control. Figure 7 shows a beam specimen in the testing machine. The beams are loaded until failure is detected and the applied load and resulting deformation is recorded.

Figure 8 gives the results of the experimental investigation. Figure 8a compares the measured mid-point deflections on the x -axis against the applied load on the y -axis. The black dashed line indicates the design load. For the tested

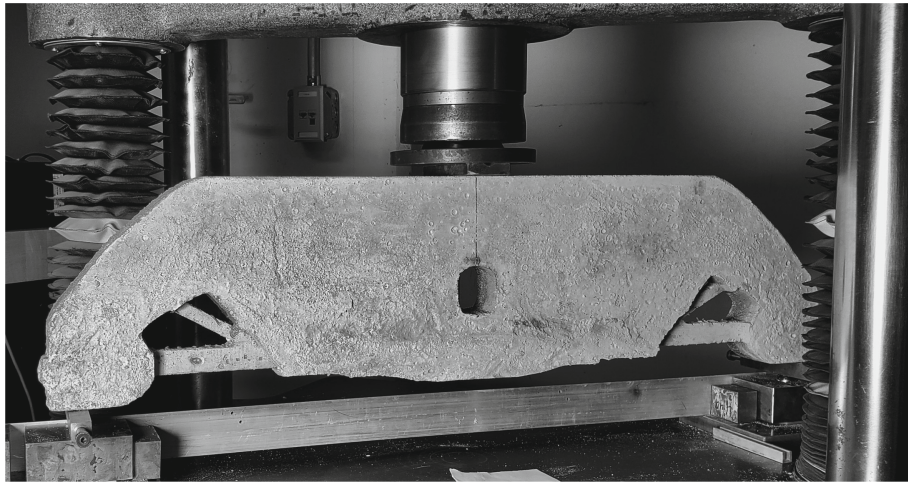


Fig. 7. Experimental set-up used for testing of all beam specimens.

beam specimens in this work, there is seen to be little variation between specimens of the same design. Additionally, brittle failure is observed for all beams without prominent display of ductility or steel yielding. All beams in this work are seen to fail significantly below the design load of $P = 88.9$ kN (20 kips) as the observed maximum loads are in the range 26.7–40.0 kN (6–9 kips). The observed failure modes were consistent for specimens of the same beam type and are shown in Fig. 9.

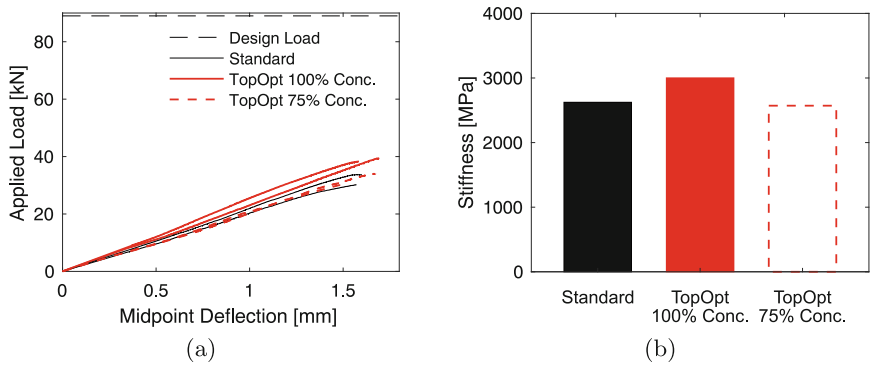


Fig. 8. Experimentally obtained results; (a) load-displacement relations for tested specimens, and (b) average stiffness at $P = 20$ kN (4.5 kips) for each of the design types.

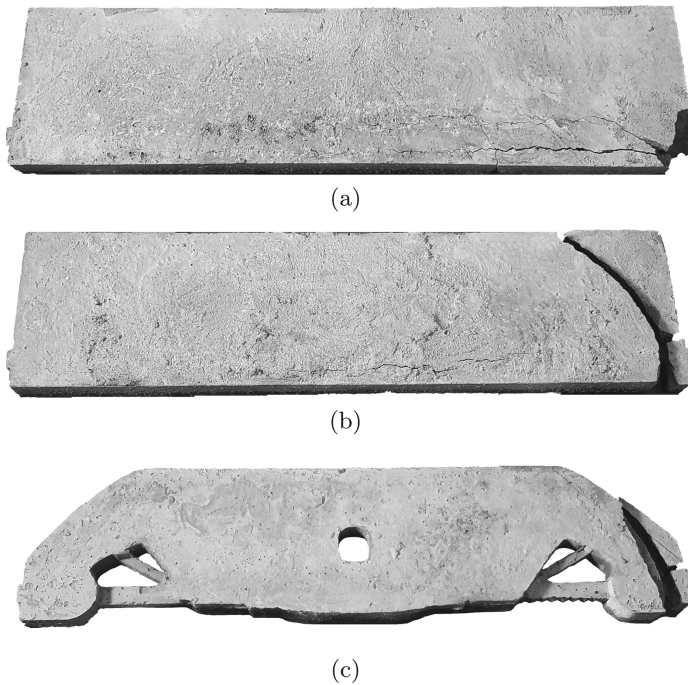


Fig. 9. Beam failures observed for (a) the standard beams, (b) the topology-optimized beams with 100% concrete volume, and (c) the topology-optimized beams with 75% concrete volume.

Upon investigation of the failed beam specimens, it is evident that a pronounced lack of bonding between the concrete and reinforcing steel plates is present. It is easily seen that the steel completely detaches from the concrete, leaving a polished surface between the two phases. Figure 10a displays an example of the polished surface of the steel and the easily visible gap between concrete and reinforcement. This poor bond quality was observed for all beam specimens in the current work. The poor bond quality is surprising since it was not observed by Jewett and Carstensen [9]. The same reinforcement method was used, however a slightly differently corrugation geometry was applied herein. The corrugations in [9] is shown in Fig. 10b that illustrates the bonding of concrete and reinforcement inside a failed test specimen. This significant difference in bond quality indicates that the corrugation pattern is extremely important for steel-concrete interface along the waterjet cut edges and calls for more research.

Despite the premature failures due to improper concrete-reinforcement bonding, the results in Fig. 8 does suggest some interesting trends about the comparison of the early elastic behaviors of the three beam designs. Figure 8b therefore compares the average stiffness of the three design types at a load of $P = 20$ kN (4.5 kips). As can be seen, the topology-optimized design with 100% concrete has a higher elastic stiffness than the standard strut-and-tie design. This concurs

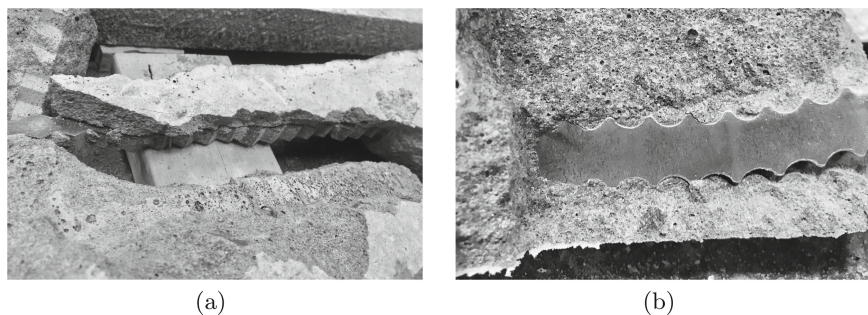


Fig. 10. Concrete-reinforcement after test from (a) the experiments in the current work, and (b) the experiments in [9].

with the conclusions in [9] and is to be expected since the objective of the herein conducted topology optimization is maximize the beam stiffness.

Not surprisingly, performance is lost when removing 25% of the concrete volume. The topology-optimized design with 75% concrete is seen to have a lower stiffness than the topology-optimized beams with 100% concrete. However, it is interesting to note that for the herein considered design case, the experimental behaviors of the standard strut-and-tie beams are nearly identical to the observed performance of the topology-optimized beams with 75% volume. Although more experimental testing is needed to rigorously support this notion, this trend indicates that significant amounts of concrete can be reduced for RC structures if topology optimization is used for the design and fabrication is done by high precision digital construction.

4 Conclusion

This work has used topology optimization as the generative design method for an experimental investigation of digitally manufactured deep RC beams. Three beam design were evaluated where one had a reduced concrete volume. In the early elastic range, the standard design and the topology-optimized beams with reduced concrete exhibited near identical behaviors. This might indicate that low weight RC design with similar properties as conventionally designed structures can be achieved.

To improve precision of the produced reinforcement, steel plates were cut by waterjet. However, in the current work, a poor bond quality of the concrete and reinforcement was obtained. This prevented a complete comparison of the tested specimens. More experimental testing is therefore needed to underbuilt the performance comparisons made in this work, and to rigorously investigate if the governing failure modes are different from those observed in conventional RC design. Additionally, more investigation of corrugation patterns is recommended if steel plates are to be used as reinforcement in future studies.

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Studying the Bond Properties of Vertical Integrated Short Reinforcement in the Shotcrete 3D Printing Process

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Abstract. Additive manufacturing techniques in construction open up new possibilities with regard to geometric complexity as well as structural and material efficiency. However, at this point in time the integration of reinforcement is still subject of research. In the presented experiments, an integration of short reinforcement bars perpendicular to Shotcrete 3D printed layers is investigated.

The focus of this study is on the bond quality and the mechanical characterization of the bond behavior between reinforcement and surrounding material for different vertical integration techniques. In this context, three methods are investigated: (1) direct insertion into the printed concrete, (2) insertion into a grouting mortar and (3) screwing the bar into the printed concrete. Steel and carbon reinforcement bars with a diameter of 12 mm are surveyed. The bond of the inserted reinforcement bars is analyzed mechanically by using standardized pull-out tests. Additional micro level analysis of the bond is performed by evaluation of computer tomography images. Directly inserted reinforcement bars show a reduced bonding compared to the other techniques due to a process-related cavity between the reinforcement and the surrounding material. By using the grouting mortar as well as by screwing the reinforcement, a significant increase of bond is achievable.

Keywords: 3D printing · Shotcrete 3D printing · Reinforcement · Mechanical properties · Bonding zone analysis

1 Introduction

Additive manufacturing techniques allow the automated production of nearly arbitrarily shaped components made of different materials. Based on concrete, numerous techniques for an additive manufacturing of unreinforced components have recently been developed. They demonstrate the huge potential of additive manufacturing techniques for the construction industry [1–5]. However, the production of specific static-constructive components represents an important next step in the development of these manufacturing methods. In this context, the integration of materials, being able to absorb tensile forces, is indispensable to create load-bearing structures.

It is necessary to develop combined additive manufacturing methods that maintain the freedom of form given by the additive manufacturing process while enabling a good bond of the reinforcement element to the surrounding material. Therefore, the following investigation focuses on the integration of short reinforcement elements in the Shotcrete 3D Printing process (SC3DP), using three different methods: a) direct insertion, b) insertion into grouting mortar, c) screwing of reinforcement bars into produced specimen perpendicular to the layer direction, Fig. 1. In this context, the bond properties of vertical integrated short reinforcement bars are examined for the named insertion techniques. The quality of each reinforcement method is evaluated by analyzing the macroscopic mechanical properties as well as additional computed tomography images to assess the quality of the bond between concrete and reinforcement.

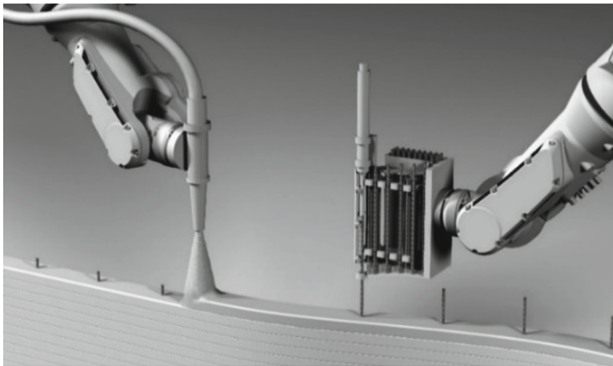


Fig. 1. Vision of a SC3DP process with an automated, robot-guided integration of short reinforcement bars perpendicular to the layer direction (Visualization by L. Ledderose, TU Braunschweig).

2 Reinforcement Methods for Digital Fabrication with Concrete

The integration of reinforcement elements in the additive manufacturing process is currently a new field of research. Within this context, numerous concepts with variable degrees of automation have already been investigated in research projects.

Contour Crafting produces in a first step lateral walls, which serve as an additive manufactured lost formwork. In a further manufacturing step, the reinforcement structure is inserted manually into the created cavity and cast with concrete. Following on from this idea, another novel reinforcement concept is developed, where individual prefabricated steel elements will be assembled automatically [6].

Another project pursues the idea of pre-stressed reinforcement in order to bear off the tensile forces acting on additively manufactured concrete components. In this case, printed concrete elements are manufactured and subsequently pre-stressed with steel reinforcement bars [7]. This technique is used by Eindhoven Technical University, which built a bridge for pedestrians in an additive manufacturing process [8].

The reinforcement process of the Chinese company HuaShang Tengda is based on the manual prefabrication of reinforcement structures and the extrusion of concrete on both sides around the reinforcement [9]. Smart Dynamic Casting [10] is a further example of the integration of prefabricated reinforcement. Here, reinforced concrete facade mullions were manufactured using slip forming technology.

The project Mesh Mould by ETH Zurich [11] pursues the automated production of prefabricated reinforcement. In this process, the production of the reinforcement is performed by a robot. Herewith, the manufacturing of free-form and precise components is enabled. The reinforcement structure manufactured is filled and finished with a concrete.

A further approach to bear tensile forces or to generate a ductile component failure is the integration of short fibers into the extruded concrete strands. Hambach [12] uses fibers during the extrusion process and was able to achieve an improved bending tensile strength in this way. A first approach for reinforcing 3D printed concrete components, by automatically integrating a continuous wire into the extruded concrete strand, was investigated at TU Eindhoven [13]. It was shown that the behavior of elements, reinforced with a wire, is comparable to the performance of reinforcement without profiling in additively manufactured strands.

An innovative approach to the additive production of reinforcing elements is offered by wire and arc additive manufacturing (WAAM), e.g. gas metal arc welding (GMAW). Depending on the selected material and process parameters, it is possible to manufacture metal bars of different thickness, length, shape, surface quality and material properties. First attempts to produce reinforcing bars using GMAW were made at TU Dresden [9, 14].

3 Materials and Methods

3.1 Printing Materials and Reinforcement Bars

The cement-based materials used in this series of experiments consists of two different types of Ordinary Portland Cement (OPC) and a quartz sand with a maximum grain size of 3.15 mm, and 0.6 mm respectively. A detailed overview of all used components and chemical admixtures is given in Table 1. For the reinforcement of the printed concrete specimens, bars of steel and carbon with a diameter of 12 mm were used. Technical data on the used reinforcement bars are shown in Table 2.

Table 1. Mixture compositions of used mortar.

Component	Shotcrete material	Grouting mortar
Portland Cement (CEM I 52.5 R)	600 kg/m ³	–
Portland Cement (CEM I 52.5 N)	–	600 kg/m ³
Ground limestone	97 kg/m ³	97 kg/m ³
Aggregate, d = 0–0.6 mm	–	1258 kg/m ³
Aggregate, d = 0–3.15 mm	1258 kg/m ³	–
Water	270 kg/m ³	270 kg/m ³
Stabilizer	0.1 M.-%	–
PCE superplasticizer	0.4 M.-%/cement	3.0 M.-%/cement

Table 2. Technical data for reinforcement bars according to technical data sheets.

	Threaded steel bar	Threaded carbon bar
Material	Steel (500/550)	Carbon Fiber Reinforced Polymer
Diameter	12 mm	12 mm
Total length	400 mm	400 mm
Cross-section	113 mm ²	113 mm ²
Weight	0.89 kg/m	0.18 kg/m
Yield load	504 N/mm ²	–
Ultimate load	548 N/mm ²	>2.100 N/mm ²
Shear-strength (longitudinal)	–	52 N/mm ²
Shear-strength (transversal)	–	260 N/mm ²

3.2 Specimen Preparation and Integration Methods

Within the framework of the presented investigation, the integration of short reinforcing bars vertically to the layer orientation of printed samples is studied. For sample production, a small lab-scale SC3DP unit (SAMMI, Smart Additive Manufacturing Material Investigator) was used [15, 16]. For achieving a sufficient specimen height of about 120 mm, four material layers were applied. The total specimen length was 300 mm. Based on the processing parameters, the sample width results in approx. 150 mm. The reinforcement bars ($d_{\text{rebar}} = 12$ mm) were inserted to a depth of 100 mm. All rebars were inserted vertically to the layer's direction in the middle of the samples surface, Fig. 2. In order to obtain a bond length of $5 \cdot d_{\text{rebar}}$ ($= 60$ mm) according to [17], the integrated rebars were decoupled in the upper section by inserting a 40 mm long plastic sleeve. Three different insertion methods were investigated, Fig. 2:

- direct insertion* of the rebar into the printed concrete: In this method, the rebars were uniformly pressed into the specimen using a guide tube arranged above the specimen.
- insertion into a grouting mortar*: A hole (diameter of 16 mm) was pressed into the specimen. Subsequently, a fine, very flowable grouting mortar was injected into the hole. Then the reinforcement bar was inserted into the grouting mortar with light poking movements.
- screwing* of the reinforcement bars into the concrete: To screw the bar corresponding to its thread pitch, the vertical movement was synchronized with the rotational speed of the bar. For this reason, the rebar was slowly screwed with a constant rotational speed through a suitable threaded socket into the concrete surface.

After finishing the reinforcement integration, there was no direct movement of the samples to avoid transport-related damage to the bond. Until mechanical testing, all samples were stored for 28 days covered.

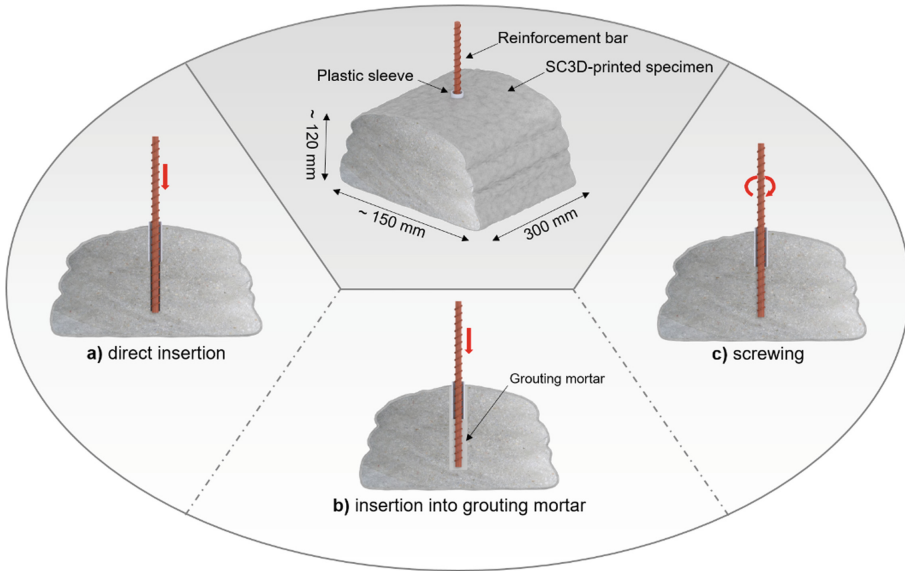


Fig. 2. Illustration of the three insertion methods: a) direct insertion, b) insertion into grouting mortar and c) screwing.

3.3 Testing Methods

Visual, mechanical and image-based investigations were used to study the effect of different integration methods on the bond behavior of vertical integrated rebars to the surrounding material.

Mechanical Tests. Mechanical tests were performed 28 days after production by using force-controlled pull-out tests according to RILEM RC6 with a load rate of 72 N/s [17]. The mechanical characteristics were determined on a hydraulic testing machine (Walter&Bai).

Micro Computer Tomography (μ CT). In order to obtain information on the bond surface between rebar and surrounding material in a non-disturbed state, μ CT-images were taken for each integration method on the carbon bars (GE phoenix, voltage 160 kV, current: 250 μ A, number of images: 1000, voxel size 0.11–0.12 mm).

4 Results and Discussion

This study focusses on the mechanical analysis of steel reinforcement bars. Therefore, the visual observations are compared and discussed with the mechanical results. In a further step, the transferability of the findings to the carbon bars is checked in order to compare and discuss the μ CT images with the steel specimens.

4.1 Maximum Pull-Out Force

The results of the pull-out tests for the integrated steel and carbon rods are shown in Fig. 3. For directly inserted steel reinforcement bars, the results of the pull-out tests showed the lowest forces. These samples failed at an average pull-out force of 11.3 kN ($\sigma = 3.3$ kN). By inserting the specimens into the grouting mortar as well as by screwing bars into the concrete, a significant increase of the required pull-out forces could be achieved. By inserting the bars in the very flowable grouting mortar, the average pull-out force could be increased by 68% to 19 kN ($\sigma = 0.9$ kN). By screwing the bars, pull-out forces similar to those of the samples inserted into the grouting mortar could be achieved. On average, the loads reached 19.5 kN ($\sigma = 2.5$ kN). For some samples, the pull-out tests did not lead to a slipping failure, and lead to a splitting of the sample instead. Since the pulled and split samples show mechanical results in the same force range, it is assumed that there is no crucial effect on the maximum pull-out force.

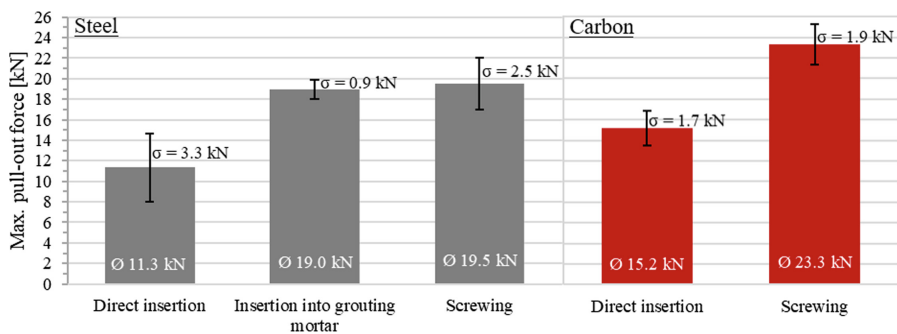


Fig. 3. Results of the pull-out tests for steel and carbon bars ($n_{\text{steel}} = 3$; $n_{\text{carbon}} = 2$).

Mechanically, the carbon bars show the same trend from direct insertion to screwing, Fig. 3. The directly inserted specimens had an average pull-out force of 15.2 kN. By screwing them in, this value could be increased to an average pull-out force of 23.3 kN. Unfortunately, the carbon bars inserted into the grouting mortar were damaged during the production process, which caused the mechanical results to be unevaluable.

4.2 Visual Inspection of Bonding Zone After Pull-Out

Even on a visual basis, severe differences in the bond surface of the test specimens are observed depending on the integration method.

The directly inserted rebars show a very irregular bonding zone, Fig. 4a. The thread texture of the inserted rebar cannot be seen in the surrounding material, which is in line with existing findings from literature [18]. Reference [18] also observed that a direct insertion of a rebar into printed strands creates a large number of voids and entrapped air around the inserted bar.

Within the present study, a void between rebar and surrounding material could already be observed on the top side of the samples after the direct insertion of the bar into the fresh concrete. Especially in the lower part of the reinforcement bar, residues of concrete between the reinforcement ribs are visible. In the upper part of the rebar, there is barely material in between the reinforcement ribs. Hence, the material does not bond over the entire integration depth, which causes the low pull-out forces.

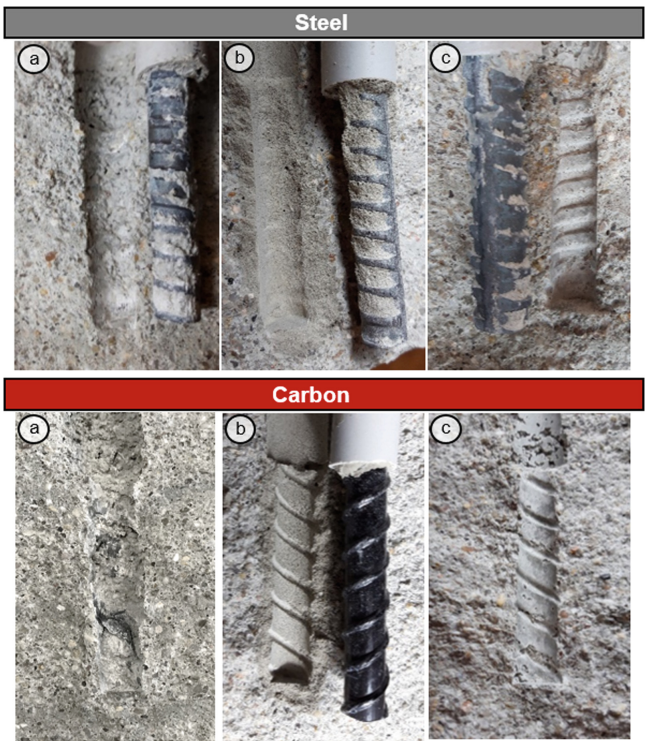


Fig. 4. Pictures of the bonding zones after pull-out of test specimens with integrated steel and carbon bars ($d = 12$ mm) for a) direct insertion, b) insertion into a grouting mortar and c) screwing.

The samples inserted into the grouting mortar show a uniform bonding zone, see Fig. 4b. The structure of the rebar is slightly projected in the grouting mortar. The spaces between the reinforcement bar ribs show uniformly sheared residues over the entire integration depth.

The screwed rebars show a clear thread formation in the printed concrete, see Fig. 4c. Especially on the upper sides of the ribs sheared material can be seen. This leads to an improved bonding. Due to the smooth surface of the carbon bars, hardly any residues could be found on the pulled out bars.

There is a correlation between the characteristics of the bonding zone and the higher pull-out forces for the insertion into a grouting mortar and the screwing method, compare Fig. 3.

4.3 Inspection of Bonding Zone Before Pull-Out

In order to obtain information on the bonding zone between reinforcement bar and surrounding material in a non-disturbed state, the inserted carbon bars were analyzed by micro computed tomography (μ CT), Fig. 5. This allows an enhanced interpretation of the mechanical testing results. Due to the high atomic number and density, μ CT scans of steel bars are not suitable for an examination of the bonding zone, as there are high scattering effects in this area. However, due to the good mechanical and visual correlation, the findings are transferable to the steel samples.

For direct insertion, multiplicity of cavities along the reinforcement bar are observed, see Fig. 5a. As the concrete residues in the lower area of the pulled out steel reinforcement bars already indicated (see visual inspection), a compacted zone with good bonding properties is present in the lower area of the directly inserted bars. During insertion, the threads at the front of the bar push the material in front of it by opening a cavity behind it. As a result, the subsequent threads cannot create a sufficient bond to the concrete. Hence, the CT scans confirm the irregular bonding zone already detected by visual inspection and can explain the origin of the low pull-out force.

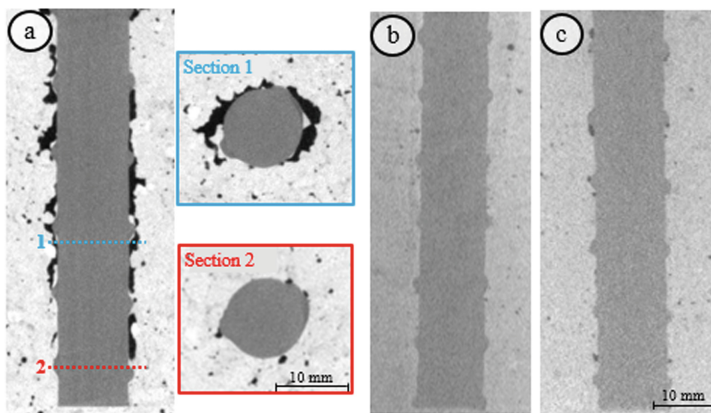


Fig. 5. μ CT-images of the bonding zones of carbon bars for a) direct insertion, b) insertion into grouting mortar and c) screwing.

A much improved bond between surrounding material and reinforcement bar is achievable by inserting the bar into the grouting mortar as well as by screwing it in. In these integration methods, an almost constant interconnection between surrounding material and rebar is realized over the entire insertion depth, Fig. 5b and c. Though, small voids are still present at certain points on the rebar. Altogether, the μ CT images

can clearly confirm the findings of the mechanical investigations. Due to the good bonding of the surrounding material to the reinforcement bar a clearly improved mechanical performance can be achieved.

5 Conclusion and Outlook

Within the framework of the presented study, the integration of short reinforcement bars vertically to Shotcrete 3D printed layers was investigated. Three methods were studied: a) direct insertion, b) insertion into a grouting mortar and c) screwing into the fresh strand. The following conclusions can be drawn from this study.

1. The quality of bonding and herewith the overall mechanical performance depends to a large extent on the used integration method.
2. A direct insertion creates voids around the integrated reinforcement bar, which leads to a weak bond and thus to a low mechanical performance.
3. The insertion of reinforcement bars in a fine grouting mortar counteracts the problems of insertion. Due to the high flowability of the mortar, a good bond between rebar and the surrounding material is achievable. Thus, for steel the pull-out forces can be increased by approximately 68% compared to the direct insertion method.
4. Screwing the reinforcement bars into the fresh concrete resulted in a clear increase of required pull-out forces compared to direct insertion. Using μ CT scans as well as the evaluation of the sample cross-sections, the best material bond could be found in the bonding zone of the screwed-in rebars. However, special attention must be paid here to ensure that the velocity in the insertion direction and the rotation of the bar are synchronized with each other so that the formation of a thread in the concrete and thus a good bonding can be achieved.

The present study has shown that the insertion of short reinforcements in SC3DP-strands depicts a very promising approach for reinforcement integration in the additive manufacturing process. With regard to their practical application, these methods could be used in different ways. For a subsequent insertion of reinforcement elements into an existing component, the insertion into grouting mortar could be conceivable. Since the screwing method does not require a second material for the insertion process, it is particularly suitable for integration in parallel with the printing process.

However, the large difference between directly inserted bars and bars inserted into the highly flowable grouting mortar shows that the rheology of the surrounding material has a decisive role in the creation of good bonding properties.

Acknowledgements. Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – Project-ID 414265976 – TRR 277.

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Aligned Interlayer Fibre Reinforcement and Post-tensioning as a Reinforcement Strategy for Digital Fabrication

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Abstract. Digital Fabrication with Concrete (DFC) brings many new possibilities for the design and production of concrete structures, promising to revolutionise the concrete construction industry. While technological and material challenges have already been overcome to a large extent, there is still a lack of sufficiently mature reinforcement solutions. Therefore, most digital technologies encounter difficulties in producing load-bearing concrete members. Fibre reinforced concrete (FRC) is one of the most promising reinforcing strategies for DFC due to its capability for producing complex geometries. In conventional FRC, the fibres are dispersed randomly in the concrete matrix; for DFC applications this (i) forces to re-engineer the concrete processing (pumpability and rheology), and (ii) requires using very short and expensive fibres due to pumpability constraints. This paper presents a new reinforcement strategy for using FRC in layered DFC technologies that overcomes the stated limitations of conventional FRC. It consists in adding fibres right after the deposition of each layer of concrete in a controlled amount and orientation and providing a post-tensioning reinforcement in the perpendicular direction. The mechanical behaviour, as well as the potential and first implementation steps in the Concrete Extrusion 3D Printing and Eggshell technologies under development at ETH Zurich, are discussed. The mechanical results show a significant increase in tensile resistance of the aligned interlayer fibre reinforcement compared to conventional FRC. However, for large-scale applications, the main loads still need to be carried by post-tensioning reinforcement.

Keywords: Digital fabrication with concrete · Concrete structures · Fibre reinforced concrete · Fibre alignment · Post-tensioning

1 Introduction

The construction industry has a highly negative impact on the environment (e.g. energy usage and CO₂ emission) [1] and is lagging far behind many other industrial sectors in terms of productivity and digital development [2]. New technologies, such as digital fabrication with concrete (DFC), could help to overcome these shortcomings by opening the way for more sustainable and efficient construction.

In DFC processes, concrete structures are produced with very thin or no formwork at all, and a robotic system places the concrete in an additive manner. This results in (i) the reduction or elimination of the use of formwork systems, (ii) the possibility to place material only where it is needed, and (iii) the production of structurally optimised complex geometries at no extra cost [3].

However, while the technological and material constraints of these technologies have already been overcome to a large extent, there is still a lack of mature reinforcement strategies allowing to produce load-bearing structural elements. Therefore, digital fabrication technologies have been applied so far mostly to produce non-load bearing structures or structures whose structural functionality merely corresponds to that of masonry walls [4]. To make a real impact in the mass market, this lack of load-bearing capacity of digitally fabricated concrete elements needs to be addressed. A possible solution consists in the use of fibre reinforcement since fibres generate a post-cracking tensile strength and at the same time do not limit geometric complexity. DFC offers new possibilities for using fibre reinforced concrete (FRC) not only as fibres randomly dispersed in the matrix, but to deliberately place the fibres in combination with additive manufacturing processes.

This paper first addresses the need for reinforcement in concrete structures and the current state of the art of reinforcement strategies for digital fabrication. Afterwards, two digital fabrication processes developed at ETH Zurich, which are well suited for interlayer fibre reinforcement and the difficulty of adding fibres to the concrete matrix itself are introduced. Subsequently, the general concept and the structural behaviour of aligned interlayer reinforcement are presented. This reinforcement approach is then applied in two case studies to the two digital fabrication processes.

Most materials used for DFC are fine grained concretes, since the maximum aggregate size is below 4 mm. However, for the sake of simplicity, this paper only refers to the material as concrete.

2 Digital Fabrication of Concrete Structures

2.1 Reinforcement for Conventionally Cast Structures

In conventionally reinforced concrete structures, steel and concrete act as a composite material where, under loading, the concrete carries the compression forces, while the reinforcement is loaded in tension. The reinforcement is not only required for the ultimate limit state but also as ‘minimum reinforcement’ to provide ductility, limit crack openings and avoid brittle failures [5]. Normally, conventional reinforcement is placed as passive steel bars in the formwork, and afterwards, the concrete is cast around

it. To resist high loads and limit deformations (e.g. in bridges), passive reinforcement is usually accompanied by active prestressing reinforcement, which consists of high strength steel tendons that are placed and grouted in ducts either inside or outside the concrete structure.

Designing and building concrete structures using conventional reinforced concrete is regulated by building codes, and the construction methods have been optimized for decades. However, novel innovations such as fibre or textile reinforcement have hardly found their way into the mass construction market. Research on FRC dates back decades [6], but so far, applications in the construction industry are limited mainly to slabs on ground and secondary structural elements such as facades, pavements or (often temporary) tunnel linings. This limitation is mainly due to the reduced performance of fibres for moderate, practical fibre contents that cannot be increased substantially without severely affecting the workability of the FRC mixes. One particular issue of the structural performance of FRC is that in conventionally cast concrete, the effectiveness of the fibres is reduced because they are randomly dispersed and orientated in the concrete matrix, and design strengths need to be even further reduced due to the uncertainty regarding their exact location and orientation [7]. The combination of FRC with digital fabrication could offer new opportunities for the structural application of fibre reinforcement.

2.2 Reinforcement Strategies in Digital Fabrication

Most of the current applications of DFC focus on vertical elements. They typically address the production either of members with low structural requirements or of members that include additional external elements (e.g. steel frames) acting as the main support system [8]. Recently, however, the development of specific reinforcement strategies for digital fabrication has received increasing attention [4]. Some of these strategies use conventional passive reinforcement which can be placed before [9, 10] or after (e.g. lost formwork) [11, 12] the production of the concrete element. For these approaches, however, the geometric freedom is compromised. Other approaches try to keep the concrete predominantly in a state of pure compression either by designing anti-funicular or arch geometries [13, 14], which is only possible in specific cases or by post-tensioning concrete elements together [15]. Even if the concrete is kept in a state of pure compression, the printed concrete itself still needs to be reinforced with at least the minimum reinforcement to be code-compliant. Reinforcing the concrete itself can either be done by laying a steel cable into the concrete during production [16, 17] or by adding fibres to the concrete mix [18–20]. The latter, however, has so far only been applied with short fibres.

2.3 Digital Fabrication with Concrete at ETH Zurich

At ETH Zurich, two DFC processes suitable for the reinforcement strategy discussed herein, Concrete Extrusion 3D Printing (CE3DP) and Eggshell, are currently being researched extensively.

CE3DP was developed in an interdisciplinary manner with the goal of achieving high-printing speed for fine-resolution custom shapes that cannot be fabricated with

any other conventional concreting technology. The parallel developments of design strategies, material formulation, hardware and robotic control were therefore aligned to achieve this goal. The system consists of a fluid concrete formulation suited for pumping, which is intermixed, in-line, with an accelerator following the set-on-demand processing strategy [21, 22]. All dedicated hardware components are integrated into a centralized process controlled via a robotic interface. Concrete and accelerator are delivered to the custom-built extruder for intermixing using two continuous cavity pumps. The print-tool is mounted at a 45° angle on the sixth axis of the ABB IRB 4600 robotic manipulator (Fig. 1). CE3DP can be used in the fabrication of formworks that are later on filled with conventional reinforced concrete. The method was successfully used in the prefabrication of columns [23]. Nevertheless, the geometric freedom of CE3DP can be further enhanced with active prestressing reinforcement and integrated minimum reinforcement in the printed concrete itself, as discussed in Sect. 3.

Eggshell, based on Smart Dynamic Casting [24], is a fabrication process in which a thin formwork is robotically 3D printed also using the set-on demand processing strategy, with the difference of using self-compacting concrete that flows into a thin formwork [25, 26]. By casting this fast-hardening concrete, lateral pressure exerted by the concrete is kept to a minimum. In this way, a 1.5 mm thin thermoplastic shell can be used as formwork, without any additional support. This enables the fabrication of complex, non-standard concrete parts with minimal formwork costs (Fig. 1). Several approaches exist for integrating reinforcement into concrete structures produced with the Eggshell technology. One option is to use standard, passive reinforcement which is placed inside a pre-printed formwork. This approach was used to construct a structural column carrying a timber roof structure in Esslingen, Switzerland [26]. An advantage of this approach is that standard reinforcement can be used. However, by placing the reinforcement inside the formwork as a second step, one is limited in the complexity of the formwork as the reinforcement has to be fit inside. Furthermore, as the geometry of the element becomes increasingly complex, it can be difficult to manufacture the reinforcement to the required tolerances, hinting towards the necessity of alternative reinforcement processes, such as the strategy discussed herein.

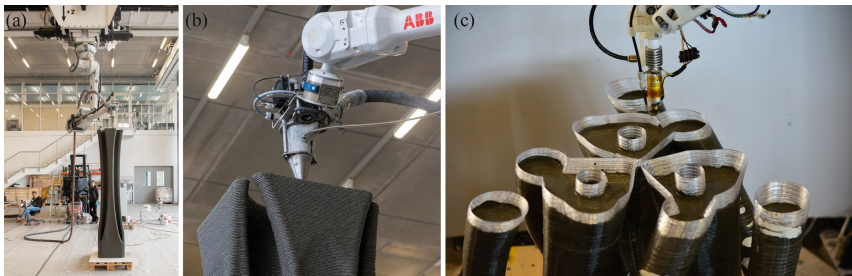


Fig. 1. Digital fabrication with concrete at ETH Zurich: (a) and (b) Concrete Extrusion 3D Printing [Photos by Axel Crettenand]; (c) Eggshell technology

2.4 Concrete Processing

DFC technologies rely on pumps for placing accurate quantities of material, predominantly using progressive cavity pumps. The main advantages of this type are their excellent flow rate control within a stroke, direct pump-rate to flow-rate proportionality and compatibility with large particles. Limiting factors are, however abrasion of the rubber stator and allowed particle size. In the typical delivery line used at ETH Zurich, the concrete pump consists of a progressive cavity pump with a rotor-stator allowing for 3 mm particles. The concrete is then pumped through a hose, fed into a mixing chamber – in which intermixing with a set accelerator occurs – and afterwards extruded or cast in the formwork. The addition of fibres to the concrete can affect, apart from the rheology of the material itself, the pumping process in several ways. Firstly, it can damage the rubber stator, a component that is critical for an accurate flow rate. Secondly, fibres can clog the delivery line in the narrowest section. Finally, for the application, fibre orientation along the flow direction should occur. For extrusion processes, this requires that the die is more than three times longer than wide and for casting the alignment would be dominated by the flow of the concrete inside the formwork, which could lead to an unfavourable alignment. In a first-order approach, we can consider for steel fibres of length L and diameter d , that their radius of gyration is $R_g = \sqrt{\frac{L^2}{2} + \frac{d^2}{8}}$, which gives for slender fibres the relationship: $L = \sqrt{12}R_g$. Here, the radius of gyration defines an equivalent particle size and thus allows predicting that for pumping fibres, up to 12 mm length could be accommodated. Further adjustments to the delivery line would be needed to avoid clogging and allow for favourable fibre alignment. Even if these limitations are overcome, the exact location and orientation of the fibres remain unknown, which complicates the design of structures.

3 Aligned Interlayer Reinforcement

The novel reinforcement strategy presented in this section, where the fibres are placed separately, overcomes the above-mentioned limitations and offers the advantage of providing control over the fibre distribution and orientation.

3.1 Reinforcement Concept

The reinforcement strategy introduced in this paper separates the reinforcement process from casting or printing. A system is imagined, where fibres are placed in between the layers of digitally fabricated concrete (i.e. for CE3DP in between the printed layers and for the Eggshell process in between the casting intervals). This concept is schematically summarized in Fig. 2. Due to the separate placement of the fibres, the processing constraints (Sect. 2.4) can be overcome, and the size of the fibres is only limited by the complexity of the geometry and not by the processing (e.g. pumping).

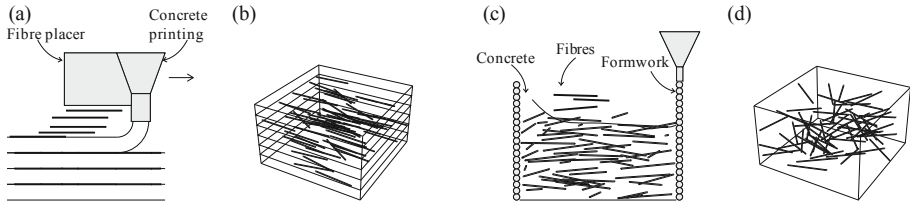


Fig. 2. Schematic sketch of the reinforcement strategy: (a) 3D concrete printing with simultaneous interlayer fibre reinforcement; (b) resulting layered concrete element with fibres in between the layers; (c) continuous filament printing and concrete casting with fibres added between casting intervals; (d) concrete element with aligned fibres in the matrix.

At the same time, this process allows to align the fibres in the direction of expected tensile stresses and grade the fibre concentration according to the structural requirements. This could result in a win-win situation, where the efficiency of fibres is increased and ‘digitally fabricated concrete’ turns into ‘digitally fabricated reinforced concrete’. This process would further permit a certain concrete cover for the fibres, which would avoid or improve aesthetic issues of conventional FRC due to corrosion of the fibres close to the surface. Furthermore, fibres have the advantage of producing smaller crack spacing than continuous reinforcements, which can be beneficial for structures where the serviceability limit state is decisive. As fibres are limited in ductility and ultimate strength, it is beneficial to add post-tensioning perpendicular to the fibre layers, which should coincide with the main direction of load transfer.

3.2 Structural Behaviour

The first investigation of this reinforcement approach involved the manual production of layered concrete elements with long steel fibres in between the layers [27]. Two sizes of samples with different fibre types and fibre configurations were produced and tested in four-point bending. The results showed that the behaviour changes from ‘deformation softening’ to ‘deformation hardening’ when the fibres are aligned. For high fibre contents, severe softening could be observed right after the peak load. This softening was due to delamination of the lowest layer and subsequent failure of the sample. It should be noted that due to this severe softening, fibres alone should not be used as the main reinforcement but rather as secondary reinforcement or minimum reinforcement. Therefore, for structural purposes, the fibres should be combined with other reinforcement, such as post-tensioning reinforcement as discussed in the following. The use of a pre-compression in the interlayers is expected to improve the behaviour of the aligned interlayer reinforcement in the post-peak phase significantly.

3.3 Feasibility of Implementation

Two studies were performed to investigate the potentials and challenges of using aligned interlayer fibres in combination with post-tensioning reinforcement. One study investigated the automation of the fibre placement in the Eggshell process, and the other study focused on the structural behaviour and the adaptation to CE3DP.

To automate the fibre placement, the particular case of the Eggshell technology was explored. A robotic prototype was built, which would disperse fibres on top of the concrete surface in between casting intervals. Figure 3 shows the resulting fibre placement on top of a concrete layer, while the robot is printing the outer shell and post-tensioning ducts. It can be observed that the fibres are not equally distributed over the cross-section. Instead, the fibres dropped in some areas all at once, while other areas were not covered. This study showed that the automation of the fibre placement is one of the key challenges and needs to be developed further. The automated process should be able to place the fibres in a homogeneous manner and simultaneously align them.



Fig. 3. Eggshell process with robotically dispersed fibres on the concrete layer.

To assess the structural behaviour in combination with post-tensioning reinforcement, a set of beams with and without aligned interlayer fibres as shear reinforcement were tested. The cross-section of the beams was chosen as a hollow cross-section with a printing path width of 45 mm and were printed vertically. During printing, an equivalent fibre content of 0.3 vol.% was manually placed in-between the layers of the webs resulting in a homogeneous, yet aligned, distribution of fibres in the beams' webs and no fibres in the beams' flanges. The beams were then turned, post-tensioned and tested in four-point bending up to failure. To activate the fibres, the beams were supposed to fail in shear. However, since there was no bond between the prestressing rods and the concrete (i.e. no grouting), the desired shear failure and activation of the fibres could not be reached. However, the ultimate load and type of failure significantly improved when fibres were placed in between the layers of the beams' webs. The beams without fibres failed in an uncontrolled explosive manner (Fig. 4.b). When fibres were present in the webs, the failure was still brittle, but the overall structure of the beam stayed intact (Fig. 4.d). For more details on the testing of the beams, the authors refer the reader to [28]. The experimental testing of the 3D printed beams showed the importance of reinforcing the printed material itself and not solely rely on prestressing reinforcement since concrete fails very brittle if the concrete itself is not reinforced.

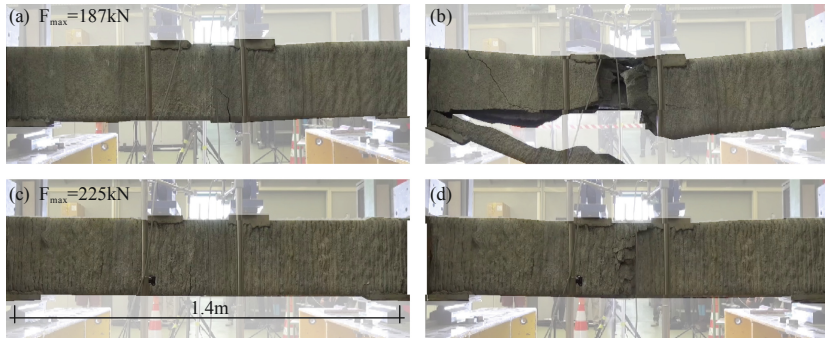


Fig. 4. 3D printed beams tested in four-point bending: (a) beam without fibre reinforcement right before failure and (b) immediately after failure; (c) beam with fibre reinforcement right before failure and (d) immediately after failure.

4 Conclusions

This paper introduces a novel reinforcement strategy for digital fabrication with concrete (DFC), in which fibres are added as interlayer reinforcement during the fabrication of concrete elements. After the production, post-tensioning reinforcement is applied perpendicularly to the interlayers to compress the concrete and carry the main loads. Aligning the fibres in between the layers results in a higher tensile strength as the efficiency of the fibres can be increased. Additionally, the type of fibres is no longer limited by processing constraints.

Possible ways to integrate the reinforcement approach in the Concrete Extrusion 3D Printing and Eggshell technologies have been discussed, identifying the potentials and challenges. The mechanical behaviour when using unbonded post-tensioning reinforcement proved promising, but brittle failures could not be avoided as all damage was localised into a single bending crack.

The automation of this strategy stills poses one of the main challenges. The seamless implementation of this or any other reinforcement strategy into DFC processes still rises serious technological challenges: Independently of the type (e.g. cable or fibres) and cross-section of the reinforcement, placement should be synchronized with the printing process and reach the same level of automation and reliability as that of the concrete processing.

This paper opens new reinforcement possibilities for DFC. Further research is, however, required. Depending on the structural application and level of automation, there are several opportunities for reinforcing DFC and building structurally informed concrete elements. However, the right reinforcement approach needs to be determined from case to case.

Acknowledgements. Authors gratefully acknowledge the students Jonathan Ensslin and Moritz Studer for their valuable support during preparation and testing of specimens shown in Sect. 3.3 and Philipp Röthlisberger and Christopher Diemand for their valuable contribution to the automation of the fibre placement. The authors would also like to express their gratitude to the

technical teams of the ‘Structures Lab’ and the ‘Robotic Fabrication Lab’ at ETH Zurich and also to the Swiss National Science Foundation, which partially funded this work within the National Centre for Competence in Research in Digital Fabrication (project number 51NF40-141853).

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Bending and Pull-Out Tests on a Novel Screw Type Reinforcement for Extrusion-Based 3D Printed Concrete

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Abstract. The lack of available reinforcement methods suitable for extrusion-based 3D concrete printing is well known. Because conventional methods using pre-placed steel bars are incompatible with this manufacturing method, several alternatives are under development. This paper introduces a novel reinforcement application method, based on screwing. Contrary to placement methods based on pushing, i.e. only a translational movement, the combination of translation and rotation inherent in the screwing motion, allows a practically void-free mechanical interlock with which a high level of bond can be attained. The concept makes use of the fact that the print mortar is still highly pliant for some time after deposition, allowing screws to be inserted without fracturing the concrete. The translational-rotational movement needs to be externally controlled, as the material at the early age does not provide sufficient resistance to pull in the screw on application of the rotation. Pull-out tests from printed and cast samples and 3-point bending tests on printed specimens showed a high bond strength and thus underline the feasibility of this concept.

Keywords: Reinforcement · Screw · 3DCP

1 Introduction

It is well known that the development of suitable reinforcement methods is delaying the employment of extrusion-based 3D printed concrete (3DCP) in structural applications [1]. The conventional method of placing reinforcement elements before applying the concrete can be used in combination with some additive manufacturing methods such as Mesh Mould [2] and Smart Dynamic Casting [3], but not in 3DCP. Thus, a multitude of strategies are under development in academic environments or tried in in-practice projects. Directly applicable strategies include post-printing application of external prestress or reinforcement elements [4, 5], combinations of 3DCP with cast concrete and conventional reinforcement [1], or (manually) embedded bars applied in pauses during the printing process [6]. However, these methods generally disrupt the printing process, limit geometrical freedom, and/or introduce additional production steps. Alternatives are under development that provide simultaneous reinforcement

fully compatible with the process, such as automatically entrained cables [7] or mesh [8], stapling metal staples into wet concrete [9] or inserting nails [10], and fibre-based solutions such as printable SHCCs [11–13].

This paper presents a novel reinforcement method based on the application of elements through a screwing motion. This application-oriented approach enables a number of reinforcement options not possible with other concepts, while eliminating some other drawbacks, as will be discussed in Sect. 2. Subsequently, we will present some experimental results from pull-out tests and 3-point bending tests to illustrate the potential of this approach.

2 Screw Reinforcement for 3DCP

The 3DCP process is characterized by a local coordinate system of 3 distinctively different directions as introduced in [14]: direction u (along the print path), direction v (perpendicular to the print path, in the print plane), and direction w (perpendicular to the print plane), as illustrated in Fig. 1. Novel 3DCP reinforcement concepts will need to be evaluated for their suitability in each of these directions. Entrained cable reinforcement, for instance, is only effective in the u -direction.

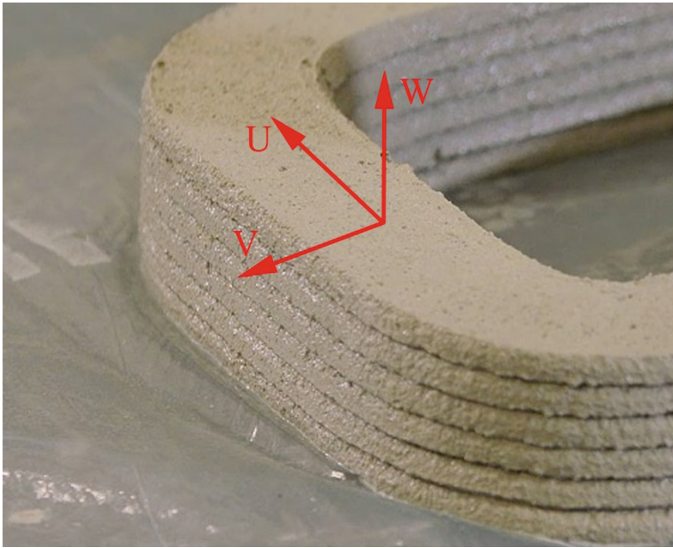


Fig. 1. Illustrations of u -, v -, and w -directions in extrusion-based 3D printed concrete.

In the v -direction, filaments are often touching either continuously when printed side-by-side, or locally, when filaments touch to support each other. In the w -direction, filaments are stacked and thus also continuously touch. The occurrence of these interfaces render the v - and w -directions principally different from the u -direction, in several ways, but certainly also in the way that structural ductility might be achieved.

The proposed screw reinforcement method seems to be particularly useful in the v- and w-directions (as well as intermediate orientations).

The principle of screw reinforcement is straight forward: a linear reinforcement element with a type of helix-shaped surface accentuation is introduced into the fresh concrete some time after deposition, by means of a combined longitudinal axis translation and a rotation along the same axis (Fig. 2). This specific motion has a specific advantage over only translation (i.e. pushing), related to the bond mechanism between the reinforcement and the matrix. In conventional reinforced concrete with ribbed bars, up to 90% [7] of the maximum pull-out resistance is generated by dilatancy, i.e. the resistance of the matrix against deformation required to allow the bar to slip out (whereas the rest stems from chemical adhesion). The high contribution of dilatancy to the overall pull-out resistance is a consequence of the mechanical interlock between the ribbed surface engulfed in the concrete that tightly packs around it during casting. In 3DCP, however, when reinforcement is applied after deposition of the filament merely by an axial translational movement, such mechanical interlock can only be achieved to a very limited extent because the high viscosity of the mortar in that state hardly allows a flow to create a tight packing. A lack of packing and creation of voids around reinforcement elements in 3DCP has also been observed with entrained cable reinforcement [15]. This problem can be overcome through the screw reinforcement method and it should be possible to obtain a high pull-out resistance – as a thought experiment, compare a nail in timber to a screw in timber: the pull-out resistance of the latter will be much higher.

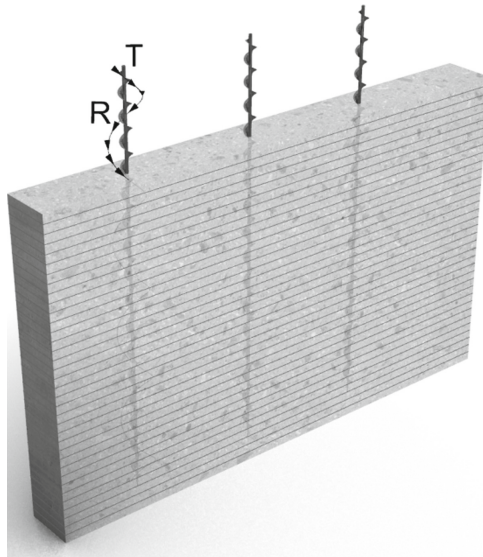


Fig. 2. Principle of screw reinforcement for extrusion-based 3D printed concrete.

The screw reinforcement method makes use of the pliant state of the fresh mortar after deposition. After deposition, the mortar will start to build up strength and stiffness, initially due to structuration [16] and later through hardening. This means that there will be a time window in which the method can be applied, since the deposited material will become too hard at some point to drive the screw in without damaging either the screw or the concrete. The time window will be highly material dependent, since printable mortars have considerably varying structuration rates and setting times. The experimental part of the current study presents some exploration of the time window for a particular mortar.

Screwing into fresh printed mortar has a distinct difference to conventional screwing, in the way the screwing motion is applied. To apply a screw, the translational and rotational movement need to be aligned, i.e. during one 360° rotation, a translation equal to the helix pitch should be performed (or vice versa). Normally (e.g. when screwing in timber, but also when applying screw pile foundations into soil), only the rotation needs to be applied by (significant) external force. The translational pull-in movement is ‘automatically’ generated by the resistance of the matrix material. The fresh printed mortar, however, is initially too weak to generate such resistance. Applying only a rotation would just lead to the screw turning around but not entering into the mortar. Thus, the translational-rotational movement needs to be externally controlled. The rotation has to be combined with a translational push inward. In the experiments presented in this study, this has been achieved by screwing through an additional round opening with the inverse of the screw thread geometry on the inside. Alternatively, the screw application could be robotically controlled to achieve the same effect.

3 Method

3.1 Materials and Equipment

Two series of tests were performed: pull-out and 3-point bending. For all samples, Weber 3D 145-2 printable mortar was used as matrix material. Fresh and hardened properties are described in [17] and [18], respectively. We can calculate from the results reported that the fresh compressive strength develops linearly from 4.6 kPa to 13.0 kPa, in a time interval from 2 to 50 min of age, while the apparent Young’s modulus increases from 42.9 kPa to 124.7 kPa. According to unpublished results, the initial set time of Weber 3D 145-2 as determined by the Vicat test, is 3 h and 40 min.

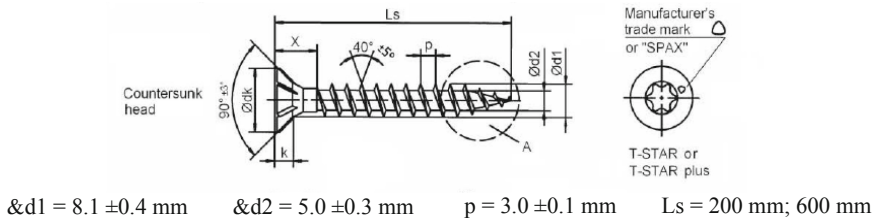


Fig. 3. Geometry of applied screws, taken from [19].

As reinforcement, self-tapping full thread stainless steel screws were used, manufactured by SPAX International GmbH. The geometry is illustrated in Fig. 3, and applied dimensions are given below the figure. Note that two lengths were used, 200 mm and 600 mm. According to the European Technical Assessment [19], the cold-rolled wire screws have a characteristic tensile strength of $F_{t,k} = 13 \text{ kN}$. Tensile tests were performed on 3 long and 3 short screws, which yielded ultimate tensile strengths of $F_{t,k} = 22.0 - 23.0 \text{ kN}$ (average: 22.5 kN). Some yielding seemed to occur above 20 kN loading.

To create test specimens, rectangular objects were printed on a large scale 3DCP facility consisting of a M-Tec Duomix mixer-pump connected to a 4-DOF gantry robot, as described in [14]. A $10 \times 60 \text{ mm}$ downflow nozzle was used, at a printing speed of 100 mm/s , resulting in 10 mm high, 70 mm wide filament layers.

3.2 Pull-Out Tests

Pull-out tests were performed on screws inserted into cast and printed mortar. In the cast specimens, the screws were applied before casting, as a reference case comparable to the conventional method of reinforcement placement. In printed mortar, screws were inserted at different time intervals ranging from 2 to 50 min after the start of the printing of the first layer. A specimen overview (including results, which will be discussed in Sect. 4.2) is provided in Table 1. In both cases, the matrix blocks were $200 \times 200 \times 40 \text{ mm}$, either directly cast to size, or obtained from printed blocks (one per series of 3 specimens) consisting of 12 side-by-side printed layers, 4 layers high, with a layer interval time of 15 s. The block height of 40 mm corresponded to 5 times the reinforcement diameter ($\& = 8 \text{ mm}$).



Fig. 4. Equipment for placement of screws.

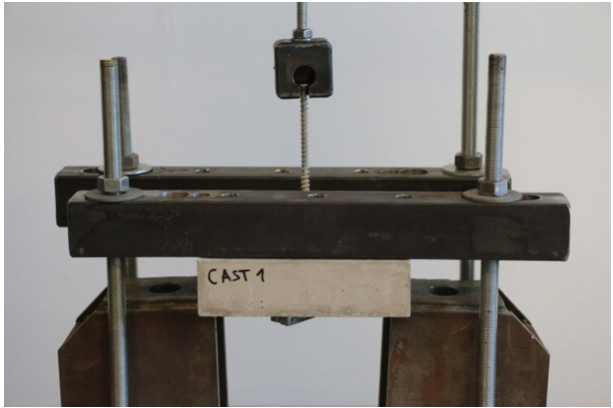


Fig. 5. Pull-out test set-up.

The 200 mm long screws were introduced through two aligned counter-fitting openings (as discussed in Sect. 2). By using 2 of such openings, wobbling of the screw tip was minimized. The openings were made in a demountable aluminium frame that was removed after a considerable length had been inserted (Fig. 4). A conventional battery-operated screw driver was used while inserting the screws. The screws were inserted far enough to come well out of the other end. The cast specimens were compacted on a vibrating table for 5 s.

Print objects were covered in plastic for 1 day after printing, and subsequently sawn into their final size before being stored under water for another 14 days until testing. The specimens were tested in an Instron universal test rig, at a rate of 20 N/s. Figure 5 illustrates the experimental set-up.

Table 1. Experimental variables and results of direct pull-out experiment on cast specimens.

Series	Qty.	Mortar	$t_{\text{screw, ave}}$ [min]	$F_{\text{pull-out, ave}}$ [kN] (rel. SD)	$f_{b, \text{eff, ave}}$ [N/mm ²]	Failure mode
#0	3	Cast	Preplaced	5.1 (5%)	5.1	Fracture of block
#1	3	Printed	2	4.7 (22%)	4.7	Fracture of block
#2	3	Printed	10	3.8 (15%)	3.8	Fracture of block
#3	3	Printed	20	3.4 (9%)	3.4	Fracture of block
#4	3	Printed	30	3.0 (33%)	3.0	Fracture of block
#5	2	Printed	40	2.4 (19%)	2.4	Fracture of block

(continued)

Table 1. (continued)

Series	Qty.	Mortar	$t_{\text{screw, ave}}$ [min]	$F_{\text{pull-out, ave}}$ [kN] (rel. SD)	$f_{\text{b, eff, ave}}$ [N/mm ²]	Failure mode
#6	3	Printed	50	3.2 (23%)	3.2	Fracture of block
#1–6	17	Printed	2–50	3.5 (26%)	3.5	Fracture of block

3.3 3-Point Bending Tests

In addition, 5 beam specimens were produced, reinforced in the w-direction with 600 mm long screws. The specimens were obtained from printed rectangular objects of 44 layers high, with a layer interval time of 32 s, and a total printing time of approximately 23.5 min. The screws were applied at $t = 32:40$, $35:50$, $37:36$, $40:00$, and $42:06$ after the start of the print. The nominal obtained specimen sizes were $l \times w \times h = 375 \times 70 \times 75$ mm. However, particularly the width varied significantly, between 65 and 75 mm. The reinforcement screw was located 20–25 mm from the bottom, in the heartline of the filament. The specimen geometry and orientation is illustrated in Fig. 6. One additional screw was applied through the print object at $t = 42:56$, to be cut into slices so that the bond over the object height could visually be evaluated. The beams were tested in a displacement-controlled 3-point bending test, at 0.15 mm/s. The span was 345 mm.

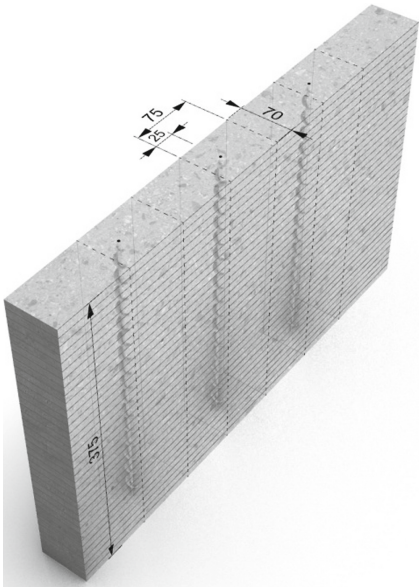


Fig. 6. Bending test specimen, as obtained from print object.

4 Results and Discussion

4.1 (Visual) Observations

During application of the screws, no deformations of the outside of the printed filament (e.g. through bulging) were observed. Also, no cracks for found after application, or before testing.

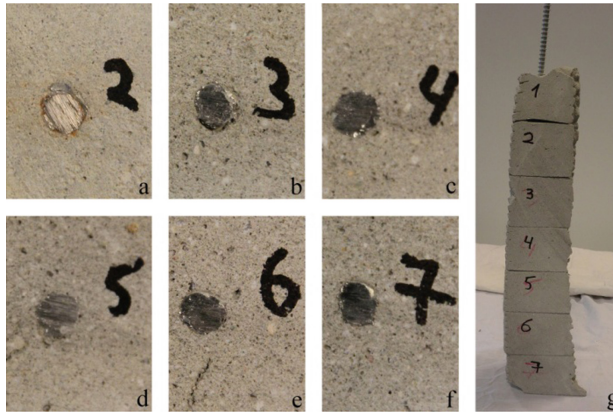


Fig. 7a–g. Sliced sample of printed concrete with screw reinforcement. The deformations on 7g is not cause by the placement of screw.

Figure 7a–g shows a reinforced sliced sample of printed concrete, cut at 6 locations. Judging from naked eye observation, the compaction around the reinforcement screws seems to be very good. No voids around the reinforcement were found. The quality of compaction around the reinforcement seems to be confirmed by the inspection of several specimens after testing, which show the imprint of the screws very clearly (Fig. 8).



Fig. 8. The imprint of specimen #2-1 after a pull-out test.

4.2 Pull-Out Tests

All specimens, both cast and printed, broke by fracture of the mortar block. The load-extension graphs are given in Fig. 9. In approximately half of the cases, failure immediate, while in the rest of the specimens some fracture occurred, but reloading was possible sometimes beyond the initial fracture load. Fracture patterns seem to indicate that the fractures originate from peak stresses around at the tips of the screw helix (Fig. 10a) (rather than overall bending failure).

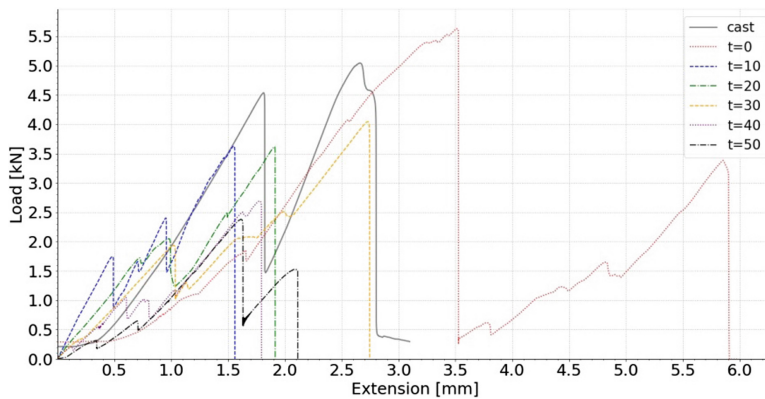


Fig. 9. Load-extension graphs of pull-out specimens. The performance of one representative specimen of each time interval has been shown.

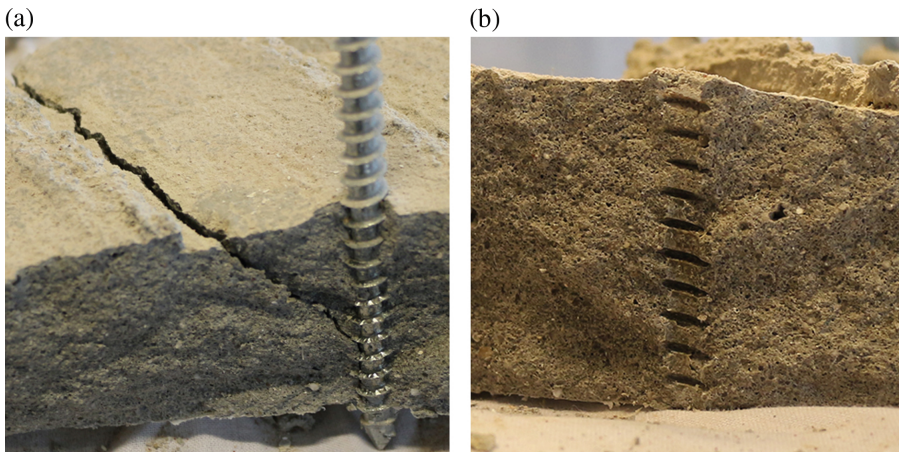


Fig. 10a, b. A crack propagation from the tip of the helix and the opposite imprint.

In any case, it may at least be concluded that the bond strength is equal to or higher than the recorded pull-out force. The experimental results are listed in Table 1 and shown as bar chart in Fig. 11. The table gives both the failure load and the average bond stress at failure, calculated as $f_{b, \text{eff, ave}} = \frac{1}{4} \pi \cdot l$ (it should be noted that the actual stress distribution around the embedded screws is much more complex, due to the screw thread geometry, but further detailed analysis of the stress distribution falls outside the scope of this experiment).

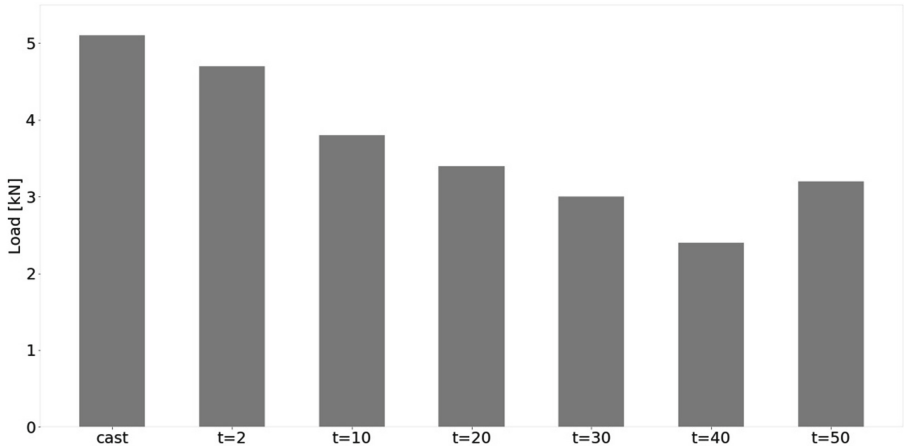


Fig. 11. Average pull-out loads of cast and printed specimens, with screws inserted at increasing time.

The results show that the average failure load of the cast specimens is higher than the average failure of the printed specimens – even though the embedment of the screws in printed concrete does not visually show defects (Sect. 4.1). Since data presented by Wolfs et al. [18] indicate no significant strength difference between cast and u-direction printed Weber 3D 145-2 mortar, it is suggested that the difference is the result of improved compaction around the screw due to the combination of casting after placement (rather than printing before placement) and compaction on a vibrating table. This may have resulted in fewer microcracks around the screw than in printed concrete, which in turn leads to a higher apparent resistance of the mortar.

In the printed specimens, the pull-out resistance seems to decrease with increasing interval time between filament deposition and screw placement – although the results are not entirely consistent and no final conclusion can thus be drawn in this regard. It is proposed that the structuring mortar might not pack as homogeneously around the intruding screw at a higher age, even if this happens before the initial set time. This can be highly relevant for the further development of this technology and deserves further study.

As a reference, the bond strength of reinforcement bars in conventional cast concrete class C30/37, with ‘good’ bond conditions and a bar diameter ≤ 32 mm, according to Eurocode 2, is $f_{b,m} = 2.25 \cdot \eta_1 \cdot \eta_2 \cdot f_{ctm} = 6.5 \text{ N/mm}^2$ ([20], after Eq. 8.2). This is considerably higher than the average $f_{b, \text{eff, ave}} = 5.1 \text{ N/mm}^2$ found in the cast specimens. Besides the fact that the current tests were performed at an age of 14 rather than 28 days, the sharp screw thread geometry might be a cause for this, as it may induce local peak stresses from which failure may originate. Stress distributions caused by the experimental set-up may also play a role. Nevertheless, we consider the obtained strength values promising.

4.3 3-Point Bending Tests

Figure 12 shows the load-displacement graphs of the 5 beam specimens. The failure loads ranged from 7.7 to 9.9 kN, with an average of 8.6 kN (rel. SD 9%), corresponding to an average maximum moment of 0.74 kNm. All specimens failed in flexural shear, which is a rather brittle type of failure, as can be recognized from the load-displacement graphs. The failure shear loads were 0.5 times the overall failure load. Figure 13 shows a typical specimen after failure in the test rig.

The maximum moment capacity of the beam sections can only be estimated, as the compressive stress-strain behaviour of the print mortar (and therefore the position of the heartline of the compressive zone) is not known in sufficient detail. In addition, there were considerable geometrical deviations in the specimens. Using the often applied rule of thumb for the internal moment lever arm $z = 0.9d$, in combination with the nominal section dimensions and the average tensile strength of the screws, the maximum moment capacity in bending would yield: $M = N_s z = 22,500 \text{ N} \cdot 45 \text{ mm} = 1.01 \cdot 10^6 \text{ Nmm}$. Although the specimens fail in shear, this theoretical capacity is almost reached, notwithstanding the geometrical irregularities. An analytical analysis of the shear load is not possible due to the complex nature of this failure mode, particularly in combination with reinforcement.

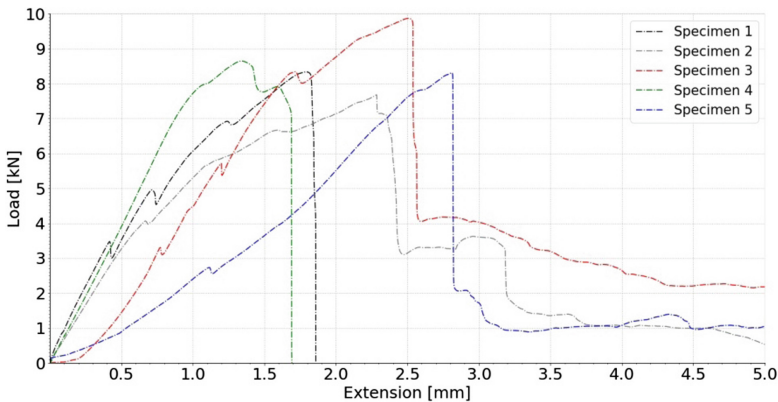


Fig. 12. Load-displacement graphs of screw-reinforced printed beams in 3-point bending (flexural shear failures).

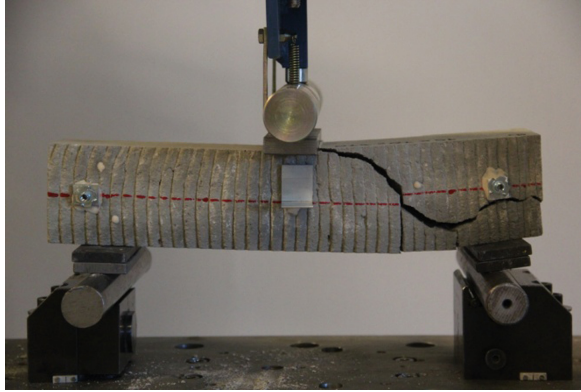


Fig. 13. Specimen 3PB- after flexural shear failure in 3-point bending test.

However, it seems very clear that the performance of the reinforcement is not governing in failure – in the 3-point bending nor in the pull-out experiments. Therefore, and considering the options to apply this method in a variety of directions and with a range of screw designs, this seems to be a promising new reinforcement concept for extrusion-based 3D concrete printing.

5 Conclusion

A novel screw-type method to reinforce extrusion-based 3D concrete printing was presented. The application through a combined and aligned translation and rotation in/around the longitudinal axis (i.e. screwing) results in a very good bond and few defects between the reinforcement and the matrix material. Pull-out tests showed this method can be applied over a considerable time span after deposition, relevant to the time range of concrete printing, although a modest pull-out strength decrease was recorded at longer time spans. Pull-out and 3-point bending tests showed the reinforcement method did not result in (premature) pull-out failure, but rather failure in the print mortar. Thus, we consider this as a positive proof-of-concept for the screw reinforcement method.

Acknowledgements. This study is part of a research project funded by Consolis SAS. Their support is gratefully acknowledged. Furthermore, the assistance of K. Nefs, D.H. Bos, and the staff of the Structures Laboratory Eindhoven in the experimental program, is highly appreciated. Additionally, Dora Plus scholarship fund provided by the European Regional Development Fund and Estonian government is acknowledged.

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Load Carrying Capacity and Failure Mode of 3D Printing Mortar Wall Panel Under Axial Compression Loading

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Abstract. A major portion of today's construction cost is attributed from a labor cost, and this labor cost tends to increase every year. Therefore, construction industries worldwide propose several modern solutions to cut back the labor cost, which consequently lead to lower overall construction cost. A 3D printing (3DP) technology using cement mortar can be one of such solutions proposed to lower the labor cost. Many research programs determining the 3DP concrete panel are being carried out. This study presents results from a scaled test of a complex shaped 3D printed wall panel with the dimension of 1.3 m height by 0.9 m width by 0.125 m thickness. The experiment aims to investigate its load carrying capacity behavior and failure mode under an axial compression loading. Test results indicate that the axial load capacity of the tested 3DP panel is significantly lower than that calculated from the material compressive strength. It is found that the geometry of the scaled panel plays an important role in the hardened performance characteristics. The 3DP wall panel was failed by the panel geometry, not by the maximum material performance due to the delaminating behavior between the layers during loading. The results from this study offers technical information used for a future optimized design of 3D printed structures in terms of shape, amount of material used, load carrying capacity, and possible failure modes.

Keywords: 3D printing · Wall panel · Mortar · Structural response · Failure mode

1 Introduction

Nowadays, a 3D printing (3DP) technology with various material types becomes ubiquitous in many industries such as 3DP medical implant applications and 3DP mechanical parts [1, 2]. However, one of the discrete examples of using 3DP that could

deliver a great contribution to our society is in construction industries. The contribution of using 3DP for construction tends to be increasing in the future. This is because one of the existing challenges in global construction industry is labor shortage. This challenge is an outcome from two main reasons. First, countries with low minimum wage labor affects the labor shortage problem. Meaningly, small number of workers desires to work in the construction field when the wage is comparable low. Second, a high minimum wage normally affects a higher cost of construction project. For example, it is reported that the labor cost could be up to 60% of total construction cost [3]. Even though the labor cost in Thailand was reported to be approximately 20% of total construction cost, research has shown that the ratio increased double in the last 10 years [4, 5]. Moreover, another benefit of 3DP technology is that it is able to create members with complicated shape without constructing any formwork, so that the 3DP technology can successfully achieve a need from an architect to produce architectural members such as fence and façade with various complex shapes. Without formwork, the extra cost from making it is negligible. In addition to architectural works implemented by the 3DP, structural works can also be produced by this technology. This study aims to investigate the structural behavior of 3DP wall panel. It is known that the 3DP material is an anisotropic material resulted from extrusion of material in layers; hence, material testing on different material axes should be conducted. The key performance characteristics include compressive strength and flexural strength, thereby these material testing programs together with axial load test of the 3DP wall were performed in this study. To perform any construction works, the permission is essential for submitting to the local governor. In general, the permission requires for the first submission of the design calculation. Pre-construction phase of any construction project must be followed the standard design code such as ACI 318 [6]. Regarding the 3DP technology, however, the design procedure does not exist. Therefore, there is a need to develop a standardized procedure or guideline for making a 3DP project structurally safe. Prior to developing the 3DP design guideline, a better comprehension on the structural behavior of 3DP structure is needed to be elucidated.

2 Materials and Methods

2.1 Materials

The 3D extrusion printing mortar was reported to require performance characteristics that are 1) pumpable, 2) printable, 3) buildable, and 4) suitable open time [7]. The 3D printing extrusion material used in this study was formulated internally. It is reported that the compositions consist of ordinary portland cement, rapid-set cement, silica fume, pulverized fly ash, hybrid fibers, crushed limestone aggregate, and accelerator/retarder admixtures. It should be noted here that the use of rapid-set cement and fly ash is a key factor influencing the open time of the cementitious materials [8, 9]. More detailed assessment of the properties can be found in Prasittisopin *et al.* [10].

2.2 Methods

2.2.1 Fabrication of Specimens

The process begins with geometry modeling of the printed element, the model was created by using a computer-aided design (CAD) software (Rhinceros 3D version 5, Robert McNeel & Associates). The solid model was transferred to the slicing software in order to slice the model to be layerwised. The thickness of each layer can be controlled as desired and the direction of printing path of the extruding nozzle is also designed by the slicing software (Cura; Ultimaker Cura). After slicing process, the sliced model was transferred into the controller of the 3DP machine and printing operation began. The 3DP process was carried out by using a Delta customized machine (WASP; Massa Lombarda). The printing area was approximately 2 m in diameter and the height was roughly 2 m. A plastic nozzle with the diameter of about 5 cm was attached to the printer. The printing process was continuous and discontinued when the printing of each element was completed.

2.2.2 Preparation of Specimens

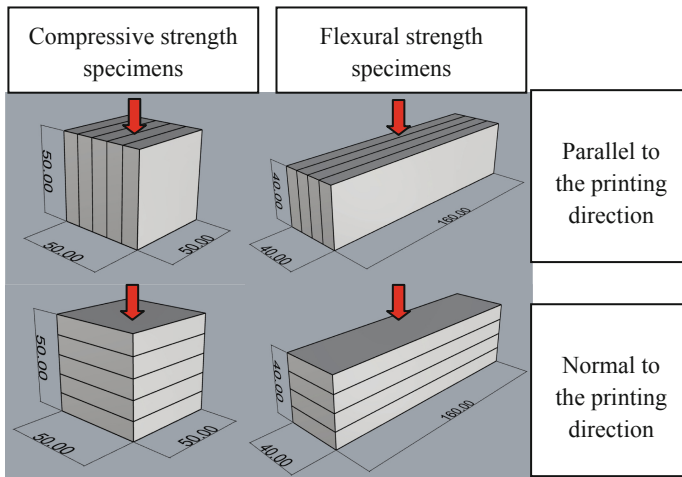
Material Scaled Specimens. The 3DP specimens were produced by printing from Delta 6-m printer. After printed for 1 day, the mortar was cut to have the specific dimension for material testing, i.e., compression and bending tests following the ASTM standards. Therefore, the hardened performance characteristics of the printed specimens were evaluated. The specimen series for testing of compressive and flexural strengths are shown in Table 1 and Table 2, respectively. Six series of tested specimens for compression and bending having the dimensions of different widths and layer thicknesses. The first columns of Table 1 and Table 2 represent a code of each specimen series tested and indicate the length, width, layer thickness, and printing direction (normal (N) or parallel (P)). Because the 3DP specimens behave as an anisotropic material, the material behavior in different directions relative to the printing direction should be investigated. The layerwise specimens tested in this study are divided into two different printing directions. First, the P printing direction of tested specimen and the N printing direction of tested specimen as shown in Fig. 1.

Table 1. Series of tested specimens for compressive strength.

Specimen series	Length (cm)	Width (cm)	Layer thickness (cm)	Printing direction	Number of samples
3 cm–0.8 cm-N	5	3	0.8	N	3
3 cm–0.8 cm-P	5	3	0.8	P	3
5 cm–0.8 cm-N	5	5	0.8	N	3
5 cm–0.8 cm-P	5	5	0.8	P	3
5 cm–1.0 cm-N	5	5	1.0	N	3
5 cm–1.0 cm-P	5	5	1.0	P	3

Table 2. Series of tested specimens for flexural strength.

Specimen series	Length (cm)	Width (cm)	Layer thickness (cm)	Printing direction	Number of samples
3 cm–0.8 cm–N	16	3	0.8	N	3
3 cm–0.8 cm–P	16	3	0.8	P	3
5 cm–0.8 cm–N	16	5	0.8	N	3
5 cm–0.8 cm–P	16	5	0.8	P	3
5 cm–1.0 cm–N	16	5	1.0	N	3
5 cm–1.0 cm–P	16	5	1.0	P	3

**Fig. 1.** Specimens for compression (Left) and bending (Right) tests with the printing directions of parallel (Top) and normal (Bottom).

3DP Wall Panel. The preparation process of the 3DP wall panel consists of 1) geometry design, 2) modelling, 3) slicing, and 4) printing.

(1) *Geometry Design.* Process of printing begins with designing the texture of the 3DP wall and the inspiration of geometric design concept of the wall in this study was derived from Durian as shown in Fig. 2. (2) *Modelling.* Rhinoceros software is used to design this model by first creating the module on the outer surface as shown in Fig. 3(a) and then each module is integrated into an outer panel surface as shown in Fig. 3(b). Another inner straight surface is created and attached with a specified distance to the outer panel. The layer thickness of the panel is then input (i.e., 125 mm for the tested wall), resulting in 3DP wall panel with a hollow section, as shown in Fig. 3(c). (3) *Slicing.* After modelling, this model is still unable be used for controlling the machine movement. It is necessary to use the software to slice and convert the model into the layerwise model as shown in Fig. 3(d). The layerwise model makes it possible to

design the path or direction of the printing. The layerwise model is then converted into the machine-controlling code (which is referred to as G-code). (4) *Printing*. It begins with mixing 3DP cement with water in the mixer in order to have the suitable workability printing material. The machine used to print the tested wall is Delta printer. The proper mortar mixtures is delivered into the plastic hopper and extruded from the extrusion nozzle. As aforementioned, the G-code of the model is imported into the machine controller. The processing parameters controlled from the machine controller are printing speed and extrusion rate. Finally, the 3DP wall panel with the dimension of 1.3 m by 0.9 m by 0.125 m as shown in Fig. 3(e) is extruded for 45 min until completed.

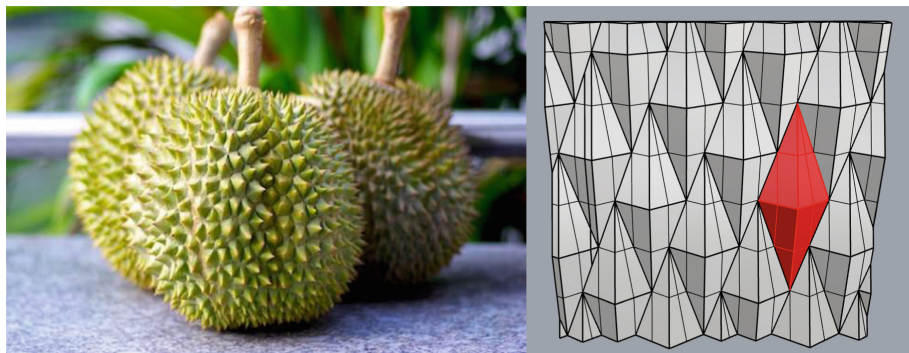


Fig. 2. Design and modeling of the texture of the 3DP wall panel. (adapted from [11])

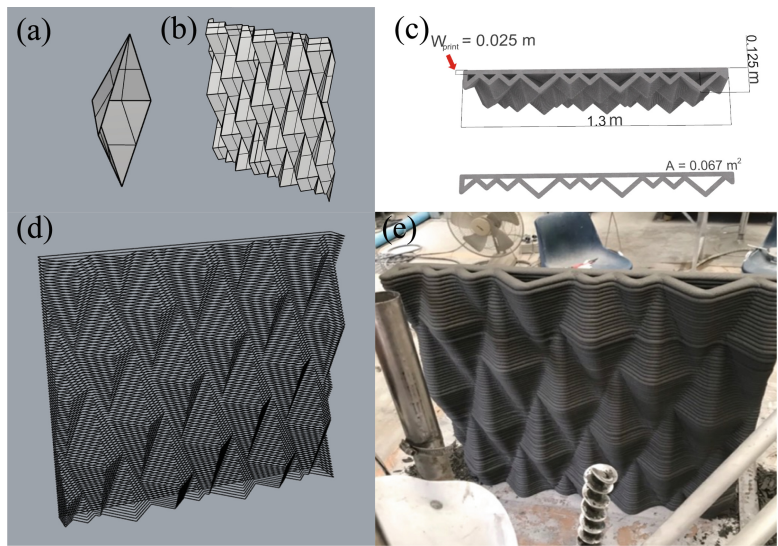


Fig. 3. (a) Module of outer panel surface; (b) outer panel surface; (c) fabrication of inner and outer surfaces; (d) layerwise file of panel; and (e) extruded 3DP panel.

2.2.3 Test Methods

Material Scaled Specimens. Test programs in laboratory were performed, including compressive strength and flexural strength tests following the modified ASTM C109 [12] and ASTM C348 [13] standard methods, respectively. It should be noted that the only modification from the ASTM standard method is using air-dried curing instead of water curing. This is for correlating the strength results of the material testing with the results of 3DP wall panel because the wall panel was also air-dried cured. Triplicate specimens were assessed for each test.

3DP Wall Panel. The testing of axial compression loading of 3DP wall panel with the dimension of $1.3 \text{ m} \times 0.9 \text{ m} \times 0.125 \text{ m}$ was conducted to evaluate the load carrying capacity and its failure behavior by using a 500-ton gravity loading machine. The rate of loading was set at 4 ton/minute. Linear Variable Displacement Transducers (LVDT) (SDP-50C; Tokyo Sokki Kenkyujo; Tokyo) were used to measure the deformation in three different directions including horizontal axis (x-axis), out-of-plane axis (y-axis), and vertical or in-plane axis (z-axis) as shown in Fig. 4. Three test parameters were assessed i.e. the maximum load capacity, deformation in X-, Y-, and Z- axes and failure pattern.



Fig. 4. Positions of LVDTs on the tested 3DP wall panel.

3 Test Results

3.1 Compressive Strength of Material Scaled Specimens

Figure 5 shows the compressive strengths of the 3DP specimens with different extruded widths and layer thicknesses, tested at the N and P directions to the printed layer. Test results indicate that the 7-day compressive strengths of all samples are not

significantly different from the 28-day compressive strengths. As mentioned earlier, this is because air-dried curing was applied to all the tested specimens. The air-dried curing instead of a proper curing such as water or moist curing was selected so that the specimens can represent the 3DP structure in the real construction where improper or no curing is provided. Comparing the 7-day compressive strengths of the 3DP specimens tested in P and N directions, results indicate that the 5 cm–1.0 cm-N, the 5 cm–0.8 cm-N, and the 3 cm–0.8 cm-N specimens have the compressive strength approximately 33% higher than, similar to, and 45% higher than those of the 5 cm–1.0 cm-P, the 5 cm–0.8 cm-P, and the 3 cm–0.8 cm-P, respectively. In addition, comparing the 28-day compressive strengths of the 3DP specimens tested in P and N directions, results indicate that the 5 cm–1.0 cm-N, the 5 cm–0.8 cm-N, and the 3 cm–0.8 cm-N specimens have the compressive strength at 28 days approximately 40% higher than, similar to, and 33% higher than the 5 cm–1.0 cm-P, the 5 cm–0.8 cm-P, and the 3 cm–0.8 cm-P, respectively. Regarding test directions, the mortars tested in P-direction have lower compressive strength than the mortars tested in N-direction. This is because cracks were formed along the interface of each printed layer in the specimens tested in P-direction as shown in Fig. 6(a). And the interface is a weak plane for the layered specimen. Therefore, cracks can be initiated prematurely in these specimens. On the other hand, cracks were formed across the interfaces (weak planes) of all printed layers in the specimens tested in N-direction as shown in Fig. 6(b).

Furthermore, comparing the 7-day compressive strength of the specimens having different layer thicknesses, results indicate that the 5 cm–1.0 cm-P specimen has the 7-day compressive strength lower than the 5 cm–0.8 cm-P by about 30% and the 5 cm–1.0 cm-N specimen has a compressive strength lower than the 5 cm–0.8 cm-N by 71%. For the 28-day compressive strength of the specimens having different layer thicknesses, results indicate that the 5 cm–1.0 cm-P specimen has the 28-day compressive strength 20% lower than the 5 cm–0.8 cm-P 20% and the 5 cm–1.0 cm-N specimen has the compressive strength 67% lower than the 5 cm–0.8 cm-N. Reducing the layer thickness of the 3DP specimens results in higher compressive strength. This is because when printing, the feeding rate of the fresh 3DP mortar is constant but the printing volume is reduced when the layer thickness reduces. This is believed to make the fresh mortar compressed and denser allowing its compressive strength to be higher. Additionally, regarding the difference of the width of the 3DP specimens, results indicate that similar and lower values of the 28-day compressive strength were observed when comparing the 5 cm–0.8 cm-N specimen with the 3 cm–0.8 cm-N and the 5 cm–0.8 cm-P with the 3 cm–0.8 cm-P specimen. There is no significant difference between the tested specimens having different widths in regard to their compressive strengths.

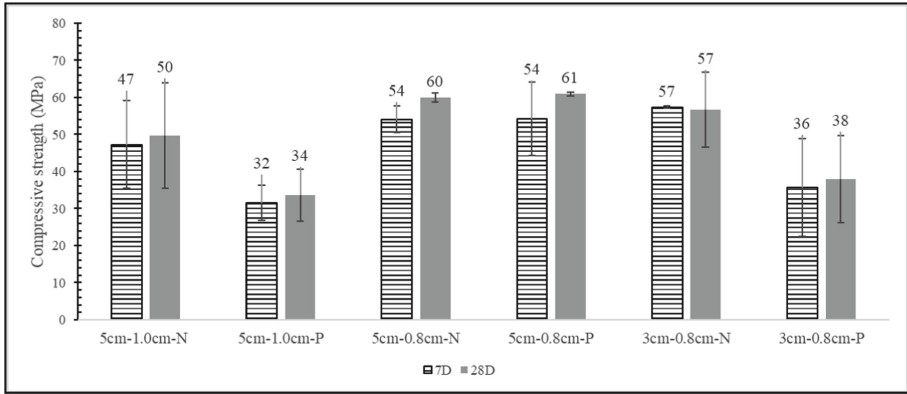
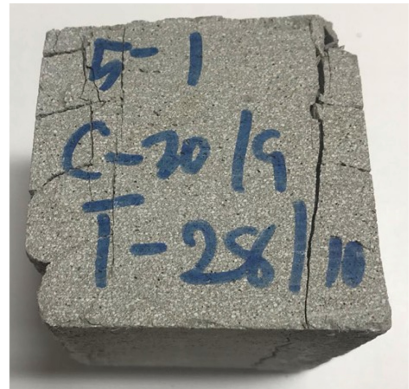


Fig. 5. Compressive strengths of all the 3DP specimens



(a) Damage pattern of specimen tested in P-direction



(b) Damage pattern of specimen tested in N-direction

Fig. 6. Damage patterns of specimens under compression tests

3.2 Flexural Strength of Material Scaled Specimen

The flexural strengths of the 3DP specimens with different extruded widths and layer thicknesses tested at N and P directions are shown in Fig. 7. Tested results indicate that the 7-day flexural strengths of the 3DP specimens tend not to be significantly different from the 28-day flexural strengths due to the air-dried curing. Comparing the flexural strengths of the 3DP specimens tested at P and N directions, results indicate that the 5 cm–0.8 cm-P, and the 3 cm–0.8 cm-P specimens has the 28-day flexural strength 40% higher, and 30% higher than the 5 cm–0.8 cm-N, and the 3 cm–0.8 cm-N, respectively. It is noted that the test results of 5 cm–1.0 cm-N and 5 cm–1.0 cm-P may not be reasonable since the flexural strength at 7 days of 5 cm–1.0 cm-P is higher than that of 5 cm–1.0 cm-N. However, the flexural strength at 28 days of 5 cm–1.0 cm-P is

lower than that of 5 cm–1.0 cm–N. The test results, apart from 5 cm–1.0 cm–N and 5 cm–1.0 cm–P, show that the flexural strength of 3DP specimens tested in P-direction is higher than the specimens tested in N-direction since the specimens in N-direction possess a higher number of interfaces between each printed layer which result in weak shear planes in the specimens. Last, regarding the flexural strength of 3DP specimens having different widths, the tested results seem not to be significantly different when the widths of specimens are varied.

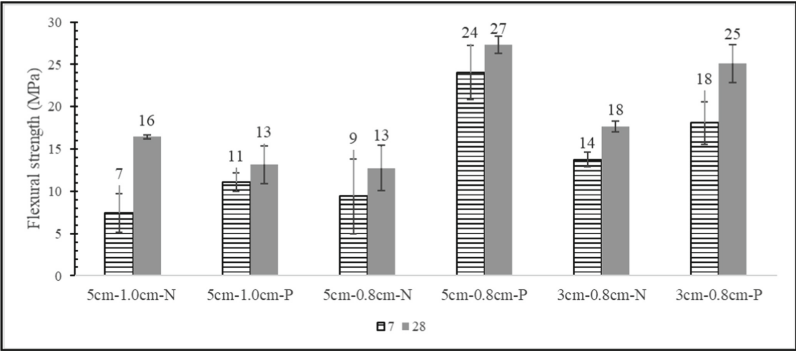


Fig. 7. Flexural strengths of all the 3DP specimens.

3.3 Compression Load Test of 3DP Wall Panel

Figures 8(a), (b), and (c) show the relationships of compressive force and deformation of the tested wall panel in X-, Y-, and Z-axis, respectively. The deformation of the panel in X-axis is almost zero. This means that only a small horizontal sliding is observed from the test. The deformation in Y-axis is up to 9 mm whilst it is about 6 mm in Z-axis where Z-axis is in the direction of the load applied. From these test

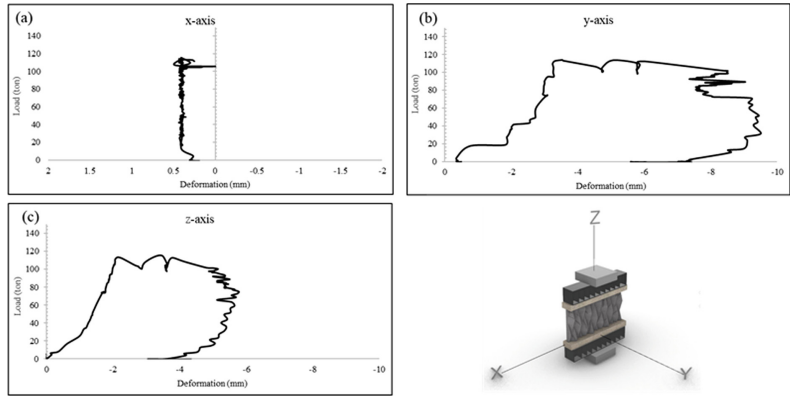
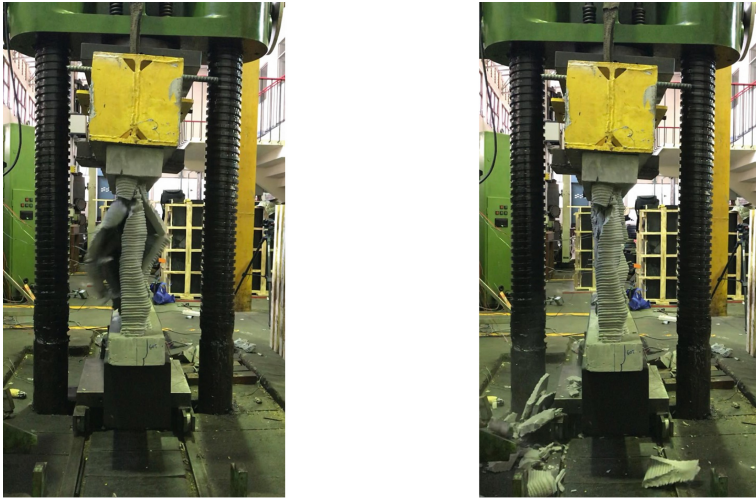


Fig. 8. Relationship between compressive force and deformation of the 3DP wall panel in (a) X-, (b) Y-, and (c) Z-axis.



(a) at breaking of 3DP concrete shell (b) right after breaking of 3DP concrete shell

Fig. 9. The bulking failure mode of the 3DP wall panel at load of 115 tons.

results, the tested wall showed larger lateral deflection than the deflection in the loading direction. The measured deformation in three axes (see Fig. 8) together with the observed failure pattern (see Fig. 9) clearly show that the tested 3DP wall with the complex shape failed by a buckling mode.

4 Discussion

In this study, the load carrying capacity of the texture 3DP wall panel was tested. The results exhibited that first crack was observed at the approximate loading value of 75 tons, locating at the outermost surface of the module, as shown in Fig. 3(a). Besides, at the loading around 100 tons, delamination behavior between each layer of the 3DP was then observed. Finally, at the 115-ton loading, the 3DP wall panel was failed. Its failure apparently exhibited buckling behavior where the shape and texture of the thin wall hollow panel governed the load carrying capacity of the wall.

The main aim is to evaluate the load carrying capacity of the texture 3DP wall panel relating to the material properties of 3DP material scaled specimens. The compressive strength of 5 cm–1.0 cm-N specimen, as illustrated in Fig. 5, was selected for this comparison because its layer thickness and loading direction are similar with the wall panel. As shown in Table 3, the load capacity calculated from material compressive strength multiplied with material area (excluding hollow area) in Fig. 3(c) is about 317.7 tons compared to 115.0 tons obtained from the test. The difference in load carrying capacity is about 2.76 times. This significant difference results from buckling failure mode of the tested wall where the shape and texture of the thin wall hollow panel governs the load carrying capacity of the wall. It can be concluded that the 3DP wall panel fails having the geometric control allowing the stress presenting in the failed

3DP wall panel less than its material strength. From these results, finite element (FE) models taking into account of the interface strength in each printed layer will be developed in the future study in order to be able to predict the actual load carrying capacities and the failure modes of any shape of 3DP wall panel.

Table 3. Load capacity of 3DP wall panel.

	Calculated from $f_c' \times A$	Testing	Difference
Load (tons)	317.7	115.0	2.76×

5 Conclusion

This paper presents information of compressive strength and flexural strength of 3DP mortar fabricated material scaled specimens, and load carrying capacity and failure mode of a 3DP wall panel under axial compression loading. The test results of the material scaled specimens and the wall panel are as follows:

- For the 3DP material scaled specimens tested at different directions, the compressive strength of the P direction was lower than that of the N direction. In contrast, the flexural strength of the P direction was higher than that from the N direction. The 3DP specimens having smaller layer thickness showed higher compressive strength and flexural strength than those with larger layer thickness higher.
- For the 3DP wall panel under vertical load, significant deformation in Y-axis (lateral direction) was detected compared to that in Z-axis (loading direction). This clearly shows that the complex geometry of the 3DP wall panel, instead of the material strength, governs the load capacity and failure mode of the 3DP wall panel. The observed failure pattern and the deformation measurement of the tested wall in three axes indicate buckling failure mode.

The actual load carrying capacity of the 3DP wall panel is significantly lower than that calculated from the material compressive strength. In order to accurately predict the actual performance of the 3DP wall panel with any shape and dimension, a sophisticated FE model of the 3DP wall panel will be established in the future study.

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Application of 3D Printed Segments Designed by Topology Optimization Analysis to a Practical Scale Prestressed Pedestrian Bridge

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Abstract. 3D printing technologies with cementitious materials have advanced dramatically in recent years. Likewise, we have also developed suitable materials with high thixotropy for layered extrusion and the gantry 3D-printing system, dealing with discontinuous geometry and multi-productions simultaneously. In this way, there have been a lot of studies particularly on material properties and printing processes so far. However, few studies have conducted structural performance testing on a large scale in a systematic manner. Hence, this structural concern is focused on and tackled in this study. The developed materials and printing system are used for the following experiments. As a preliminary test, specific characteristics such as anisotropy and creep of a layer-by-layer component are investigated for a structural design in addition to basic fresh and hardened properties. After the rational geometry is determined by topology optimization analysis, in which a practical scale pedestrian bridge under sidewalk loading is designed, its structural performance is evaluated for safety based on FEM (Finite Element Method) analysis, while considering the preliminary tests. The designed bridge structure consists of 44 segments with different complex shapes, which are printed separately, and all the segments are unified as a compression loaded structure through prestressed external reinforcement. Finally, it is confirmed whether the inherent behavior due to the laminar structure is observable in the full-scale bending test.

Keywords: Structural performance · Anisotropy · Creep · Topology optimization method · Prestressed external reinforcement

1 Introduction

We have been developing a 3D printing method for concrete construction by layered extrusion to realize a new structural design impossible by the conventional system, in addition to enhancement of its productivity and safety [1]. Our 3D-printing system is a fixed gantry type equipped with the extrusion nozzle of 25 mm diameter. It can manufacture a member with the maximum size; length 2.0 m, width 1.7 m and height 1.5 m. The advantage of this system can also deal with discontinuous geometry and

multi-productions simultaneously. It is revealed that a complex-shaped bench designed by the topology optimization method as well as a large-scale member can be produced rapidly like the original design, using our developed cementitious materials (CMs) with high thixotropy [2]. On the other hand, a major concern is that layered extrusion cannot be applied to any structural members enduring tensile force due to the difficulty of embedding rebars while extruding. As a result, possible approaches to address reinforcement integration are considered such as the following, that (a) reinforcement is arranged before manufacturing, (b) ductile printing materials such as short fibers and a reinforcement cable are incorporated during manufacturing, and (c) reinforcement is installed and then prestressed external loading is added once a structure has been manufactured [3]. However, few projects on a practical large scale, which deal with structural design, manufacturing and evaluation of its performance in a systematic manner, exist world- wide [4, 5].

Hence, we challenge such a practical scale verification project concerning the design of a prestressed pedestrian bridge with a length of 6.0 m, manufactured/printed many varieties of composed segments and unified them as a compression loaded structure through prestressed external reinforcement. The overview of this study is illustrated in Fig. 1. The respective components are further described in the subsequent sections of this paper.

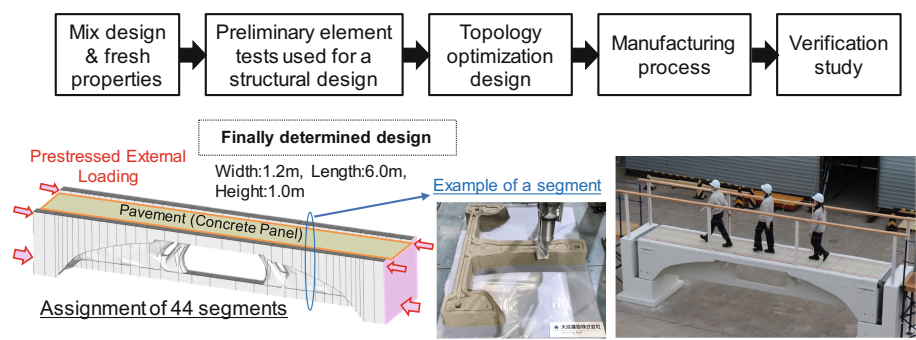


Fig. 1. Overview of this study

2 Mix Design and Fresh Properties

The mix design of the CMs with high thixotropy used in this project is presented in Table 1. The powder is cement with a rapid hardening capability through enhancement of the initial reactivity. All of the materials except for liquid admixtures are premixed before using this mixture. The value of the mortar flow test after beating a flow table 15 times can maintain between 160 and 170 mm for 120 min under a 20 °C environment.

Table 1. Mix design of the CMs used in this project

W/P [%]	Unit weight [kg/m ³]					Liquid admixtures [P × %]		
	Water	Powder	Coarse sand	Fine sand	Viscous agent	Super plasticizer	Deforming agent	Retarder
37	271	732	879	366	37	0.20	0.20	1.20

3 Preliminary Element Tests

Preliminary element tests conducted to investigate the inherent hardened properties of a laminar structure are listed in Table 2. Each size of the specimen is determined according to Japanese industrial standards. These results are applied to the following structural design. These tests include core-drilled specimens removed from multiple layers, cast specimens in molds and printed specimens by layered extrusion.

Table 2. List of the preliminary element tests

	Size of specimen [mm]	Type	Note	Index	Testing days
Compressive strength	Φ100 × 200	Core-drilled	–	CP	7, 28
		Cast	–	CC	1, 3, 7, 28
Young modulus	Φ100 × 200	Core-drilled	–	(CP)	7, 28
Split tensile strength	Φ100 × 110	Core drilled	Vertical	TPv	7, 28
			Horizontal	TPh	
		Cast	–	TC	1, 3, 7, 28
Compressive creep	Φ100 × 200	Core drilled	Loading	RL	7, 28
			Non-loading	RN	
Drying shrinkage	100 × 125 × 600	Printed	–	DP	1, 2, 3, 7, 14, 21, 28, 91
	100 × 100 × 400	Cast	–	DC	

3.1 Compressive Strength, Young Modulus and Split Tensile Strength

Core-drilled specimens are removed from the hardened laminar structures manufactured by layered extrusion and the center of the cross-section always corresponds with the filament boundary as shown in Fig. 2a. The types of split tensile strength tests are classified into vertical or horizontal planes against the loading direction as illustrated in Fig. 2b. All the specimens used in 3.1 are constantly cured at 20 °C and relative humidity (R.H.) of 60% after the age of 24 h until a given testing day. The compressive strength test is conducted onto the capped top surface including three filament boundaries. Young modulus is calculated based on the stress-strain relationship obtained in the compressive strength test. The results of compressive and split tensile strengths are presented in Fig. 3.

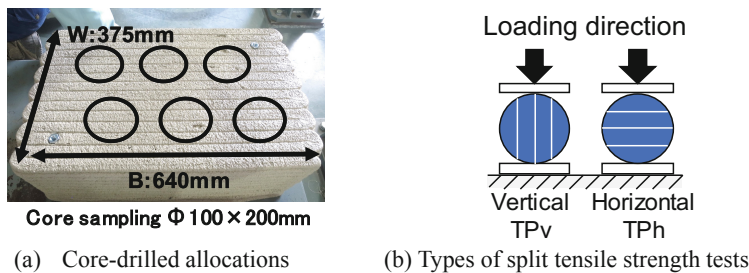


Fig. 2. Details of core-drilled specimens

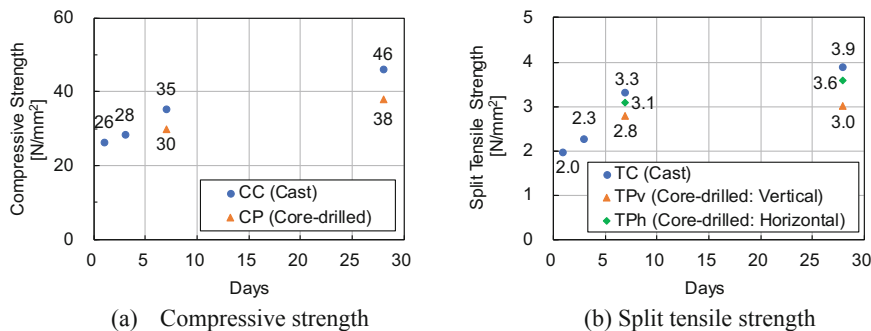


Fig. 3. Test results of compressive and split tensile strengths

The compressive strengths of core-drilled specimens (CP) are less than those of cast specimens (CC) by 10–20% at the same testing ages. The Young modulus of CP indicates 20.5 kN/mm² at 7 days and 21.7 kN/mm² at 28 days respectively. Turning to the split tensile strengths, whereas the results of TPv are less than those of cast specimens (TC) by 15–25%, TPh are less by 5–10% in a similar comparison. As a result, it suggests that the split tensile strength of such anisotropy depends on the filament plane against the loading direction, leading to a remarkable reduction in the same case in both directions.

Figure 4 shows the observations of CP, TPv and TPh specimens after the testing. In the case of CP, inclined fracture begins to evolve from the top surface like a cone and finally connects between voids contained in adjacent filaments, inducing vertical continuous fracture. Likewise, the cross-section of TPv contains horizontal voids along the filament and the voids are extended to continuous fracture on the filament plane. In short, it can be inferred that the fracture evolution induced by such voids along the filament may reduce the split tensile strength ratio of TPv/TC.

3.2 Compressive Creep

The compressive creep test in which two core-drilled specimens are vertically connected as shown in Fig. 5a is conducted under the environment of 20 °C and R.H. of

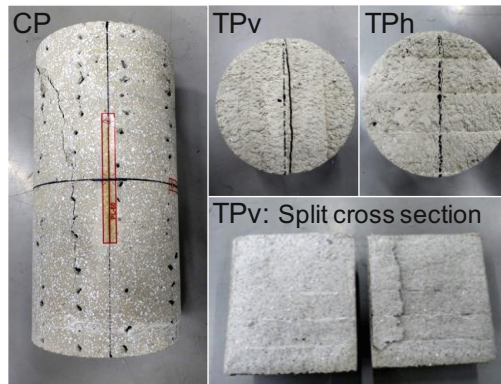


Fig. 4. Observations of CP, TPv and TPh specimens after the testing

60%. The age at which the compressive loading begins is 7 days on RL7 and 28 days on RL28 respectively. The top and bottom surfaces of the connected specimens are sealed with epoxy resin coating. The beginning of strain measurement corresponds with the respective loading start. The compressive stress of RL7 (or RL28) by loading is defined as one third of the CP strength at 7 days (or 28 days) as shown in Fig. 3 and the duration of measurement is 56 days. The total strain (ε_{at}) measurement is based on the contact gauge plug method in which the plugs are attached on 4 vertical traverse lines of a cylindrical surface per specimen (See Fig. 5a). The following result is defined as the average value of 8 traverse lines per test.

The results are presented in Fig. 5b, including the logarithmic regression curves also. The elastic strain (ε_e) shows 508×10^{-6} on RL7 and 610×10^{-6} on RL28 respectively. Incidentally, the reason why the strain of RN7 is larger than that of RN28 without loading (ε_{st}) is that the respective drying shrinkage should be eliminated before 7 days in RN7 and 28 days in RN28. Based on Fig. 5b, the creep coefficient (Φt) in a year which is calculated according to Eq. (1) results in 4.53 in RL7 and 3.34 in RL28.

$$\Phi t = (\varepsilon_{at} - \varepsilon_e - \varepsilon_{st}) / \varepsilon_e \quad (1)$$

Where ε_{at} is total strain, ε_e is elastic strain immediately after loading, and ε_{st} is strain without loading.

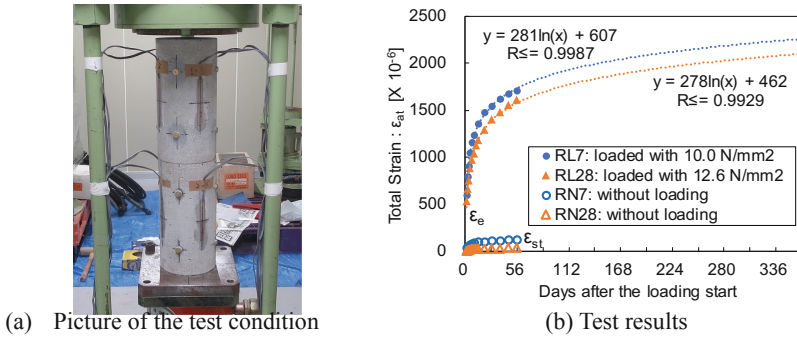


Fig. 5. Picture and results of the compressive creep tests

3.3 Drying Shrinkage

The drying shrinkage is measured based on the contact tip method. The result per test is the average value of 3 specimens. Two contact tips at intervals of 350 mm are attached by epoxy resin after the age of 24 h. The plane where the traverse line is set is the bottom in the case of the cast specimen (DC), while they are on both sides as well as the bottom in the case of the printed specimen (DP). The measurement is conducted under the environment of 20 °C, and R.H. of 60% afterwards.

The results are presented in Fig. 6. Although the results of the DCs provide a larger variation than those of DPs, all the strains range from 230 to 270×10^{-6} at 28 days and from 240 to 290×10^{-6} at 91 days. It is revealed that little strain increases after 28 days and in short the drying shrinkage tends to converge early. This tendency is similar to the result of RN28 shown in Fig. 5b.

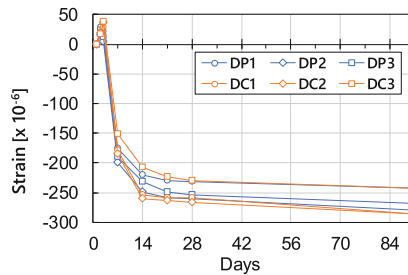


Fig. 6. Test results of drying shrinkage

4 Topology Optimization Design

4.1 Numerical Conditions and Input Data for Analysis

The original shape of a prestressed bridge studied by topology optimization design is illustrated in Fig. 7. The total size is; length 6.0 m, width 1.2 m and height 1.0 m.

Two PC (Prestressed Concrete) steel bars are installed in part of the upper flange and one in the lower one. The following three areas are considered as non-changeable design areas which are not optimized by this method; (1) the upper flange with a 150 mm thickness which is the floor of the bridge, (2) the cross-section area with 150×150 mm around a PC steel bar in the lower flange along the bridge axis and (3) the two parts at both ends with a length of 300 mm. In performing a structural design, we consider the sidewalk loading on the upper flange as 5.0 kN/m^2 which is defined by the specifications for a pedestrian deck in Japan, the dead load of this bridge and the added forces as prestressed loadings. Each 25 kN prestressed force is added to the two areas in the upper flange and 50 kN to one area in the lower flange. The numerical software used for this topology optimization design is “Inspire Ver.2019.2” which is based on elastic model and does not take account of the tensile/compressive constitutive law independently. Figure 7 includes the input data used for this analysis. These inputs are determined based on the results of the preliminary element tests.

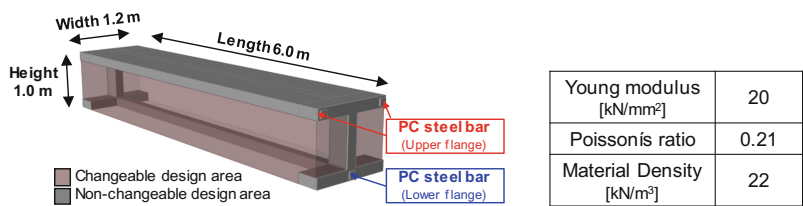


Fig. 7. Original shape, numerical condition and input data used for topology optimization design on a prestressed bridge

4.2 Optimized Result

The basic shape which is obtained by topology optimization design and the improved final shape taking into consideration workability and safety are illustrated in Figs. 8a and b respectively. The weight of the optimized basic shape becomes one fourth as much as the original shape (See Fig. 7). The final shape is determined to be changed from the basic one by making the diagonal members thicker, removing the extra parts along the lower flange in terms of aesthetic design and increasing the heights of both sidewalls to hold the pavement on the upper flange within them.

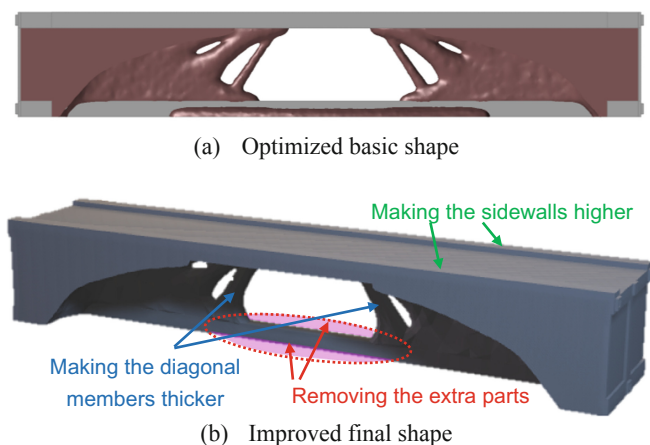


Fig. 8. Change of shape according to the design process

5 Manufacturing Process

The prestressed pedestrian bridge to be manufactured consists of 44 segments which have a variety of complex shapes as illustrated in Fig. 1. The connections among adjacent segments were carried out at least 7 days after the last segment was printed by layered extrusion. Adhesive agent made from epoxy resin was applied to each boundary between the segments. On the other hand, the prestressed loading force to unify the bridge was determined by considering the following concerns; (1) the modified creep coefficient which is calculated by the multiplication of the creep coefficient by the ratio of the actual loaded force on the bridge to the original one added in the compressive creep test of RL7 noted in Fig. 5b and (2) the drying shrinkage which occurs after 7 days in Fig. 6. As a result, the actual loaded force is determined to be increased by 10% on the value absolutely required in the structural design. The PC steel bars are sealed but the printed cavities are not filled with grout.

Figure 9 shows the change of the summation value of the prestressed forces added to three PC steel bars over time. The value at 28 days becomes 102 kN and this seems to come closer to 100 kN which is absolutely required in the structural design. Here it should be noted that the vibration observed in Fig. 9 is due to the environmental temperature change in the manufacturing room.

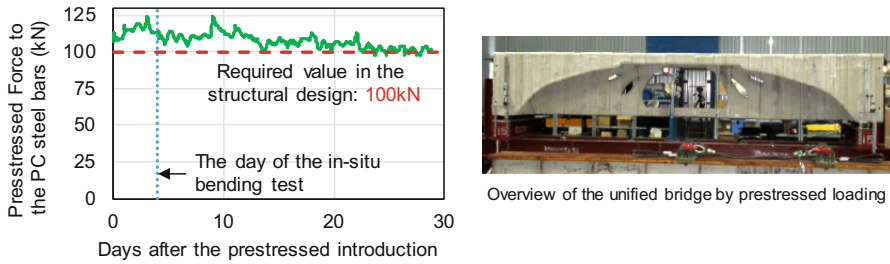


Fig. 9. Monitoring of the prestressed forces added to three PC steel bars over time

6 Verification Study

6.1 Numerical Prediction Based on FEM Analysis

The numerical prediction based on FEM analysis in which the operational condition during the exhibition for a limited time is considered and conducted to check the safety of the structural performance of the manufactured bridge. “ABAQUS 2016” is used for the analysis. A mesh model of the analysis and the loading points of the prestressed forces are presented in Fig. 10a. The following conditions are considered in two cases in this analysis; (1) the prestressed forces and the self-weight of the bridge and (2) about 12 people crowded (=10 kN) around the center of the upper flange in addition to (1) in the expected operation. The resulting loading area of 10 kN is also illustrated in Fig. 10a. The analytical result is presented in Fig. 10b.

Although the tensile stress of about 0.8 N/mm^2 occurs around the diagonal member of the central area in the maximum mean stress distribution map, the degree of the tensile stress is reduced in the operation. Consequently it is concluded that operational safety can be certified.

6.2 In-Situ Bending Test

The in-situ bending test is performed by applying a steel plate with a weight of about 1.9 kN to the longitudinal center of the upper flange. The maximum loading weight is 9.45 kN (i.e. 5 steel plates are applied). It should be noted that the concentrated load of 5.88 kN which corresponds with the even weight of the pavement over the upper flange was added to the longitudinal center before the bending test to provide the same condition as the analysis, because the actual pavement as photographed in Fig. 1 had not yet been made.

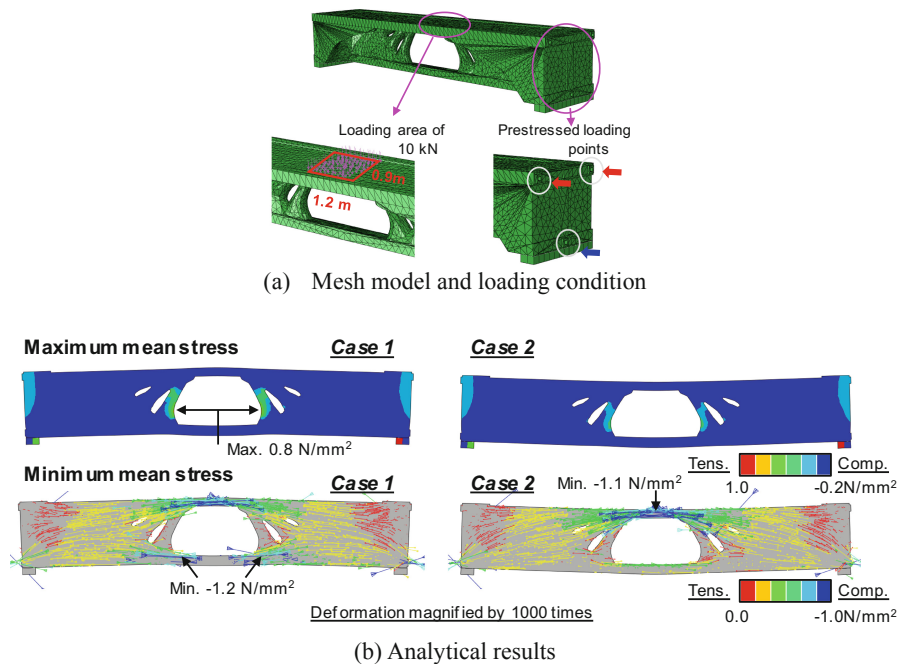


Fig. 10. Model of the analysis and the analytical results

The vertical deformations are measured just below the lower flange at the longitudinal center, at a distance of 900 mm and 2000 mm from the center and both supporting points. Likewise, it is also measured just below the longitudinal center of the upper flange. The deformation value is set as zero after the corresponding pavement weight is added.

The relationship between the loading force and vertical deformation below the center of the upper flange is presented in Fig. 11a and the distribution of vertical deformations loaded with the maximum weight in Fig. 11b, compared with the numerical prediction result. As a result, the measured values provide good agreement

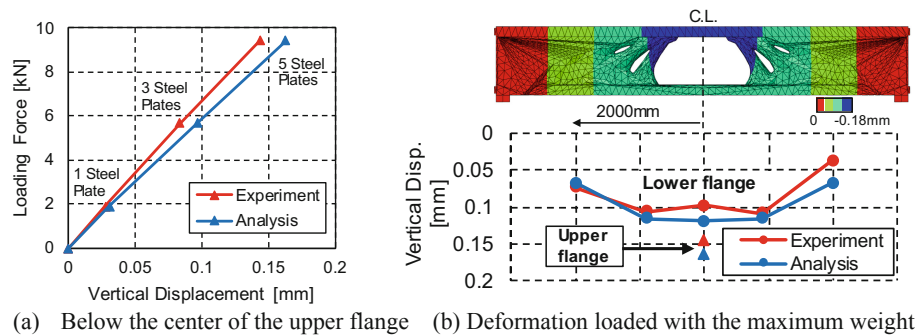


Fig. 11. Vertical deformation measured in the in-situ bending test

with the predictions. In other words, it is confirmed that any unexpected events such as fracture occurrences are not observed even in the maximum loading and the manufactured bridge behaves as an elastic unity simultaneously.

7 Conclusion

In this study, a structural verification project on a practical scale is conducted in a systematic manner. A variety of segments manufactured by layered extrusion are mutually connected and the safety in the structural performance of the unified PC bridge through the prestressed introduction is investigated. As a result, it is confirmed that the bridge is safe enough for operation during the exhibition and behaves as an elastic unity.

After the bridge is exposed to the outer environment for a long time, a proof test to check its ultimate loading force will be performed in the future.

Acknowledgement. The specific cementitious materials used in this project were co-developed with Taiheiyo cement corporation. We greatly appreciate the considerable technical contribution and mass production of the CMs which were sufficiently supplied for our common goal.

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Potential Approaches for Reinforcing Complex Concrete Structures with Integrated Flexible Formwork

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Abstract. Conventional construction of doubly-curved concrete structures is a time-, labour- and cost-intensive process. Flexible formworks have already been identified as a possible solution to produce such structures more efficiently. The KnitCrete technology developed at ETH Zurich uses 3D weft-knitted fabrics as stay-in-place formwork, which deliver multiple advantages over woven textiles due to their wider range of feasible geometries and possibility to include features and local material properties. The textile is initially coated with a fast-setting high-strength cement paste. The stiffened membrane is stable enough to serve as formwork for the final concrete layer. This paper discusses potential reinforcing strategies to guarantee structural safety and serviceability in KnitCrete structures. Possible approaches range from the use of the textile as a stay-in-place formwork as well as final reinforcement (by utilising high-strength fibrous materials such as aramid, glass or carbon fibre) to the implementation of geometric features, such as channels within the textile to guide conventional reinforcement or post-tensioning tendons. The feasibility and efficiency of the proposed reinforcement strategies have to be experimentally verified, for which a systematic methodology is proposed. Preliminary analyses of the experimental campaign show the beneficial effect of the knitted reinforcement on the cracking behaviour of the textile-concrete composite material. Additional research is needed to exploit the potential of possible hybrid solutions using short steel fibres, post-tensioning or linear steel or glass fibre reinforcement.

Keywords: Concrete structures · Textile reinforcement · High-strength fibres · KnitCrete · Digital fabrication

1 Introduction

Computer-aided design and digital fabrication have enabled a greater freedom for the definition of complex spatial geometry, for which concrete is the predominantly used building material. Due to its capability to be cast in any shape given by the formwork, concrete is highly favourable for the construction of bespoke and efficient structures.

Flexible formworks have an advantage over traditional milled and cut formworks due to their low amount of waste and reduced manual labour in the production and assembly, eventually leading to lower cost. Fabric formworks for building construction were introduced on a larger scale in the 20th century, when several patents for floor and wall systems using fabrics as main surface shaping elements were filed, e.g. [1, 2]. However, their importance in structural applications in practice is rather limited, as they are mostly used for aesthetic and non-structural purposes such as fair-faced concrete facades. Recently, researchers started again to examine the potential for larger-scale structures. West [3] investigated beams, trusses and slabs where the use of fabric formwork allowed varying shapes following the force flow. The fabric defined the closed outer shell of the structure where the concrete would inflate the formwork due to the pressure from injection. Similar work was accomplished by Orr et al. [4] and Brennan et al. [5]. Veenendaal et al. [6] developed a hybrid cable-net and fabric formwork system. The textile serves as shuttering that is placed on a tensioned cable grid and the concrete is poured directly onto this layer. This technique has been further developed and used for the production of the NEST HiLo roof prototype [7].

The KnitCrete technology [8], which has been developed at ETH Zürich within the National Centre of Competence in Research in Digital Fabrication in Switzerland, uses pre-stressed knitted textiles that are tensioned in a scaffolding frame or supported by elements such as bending-active rods or inflatables. The textile is initially coated with a high-strength cement paste, which – after hardening – serves as formwork for the following layers of concrete. Knitted textiles allow for great flexibility in the definition of spatial geometry due to their capability to vary both width and length by adding or removing loops along their internal structure to create curved and spatial geometries, whereas woven textiles are limited to single-curved patches. The technology has proven to be applicable for larger structures with the construction of KnitCandela – a pavilion that has a surface area of approximately 50 m² – in collaboration with Zaha Hadid Architects in Mexico City [9].

However, the addition of reinforcement within the construction process of such structures has not been sufficiently explored yet. Conventional steel reinforcing bars require a lot of time and manual labour for bending and installation [10] since for complex geometries, each rebar has to be placed in its unique position and orientation. This paper describes potential approaches for reinforcement strategies of concrete structures with flexible formwork, focusing on opportunities arising from knitted textiles.

2 From Formwork to Reinforcement

The approach of combining formwork and reinforcement to an integrated stay-in-place-system offers great potential to deliver a more efficient construction process with low waste and a minimum amount of temporary support elements. This section revises the possibilities that knitted textiles provide to integrate reinforcement into the formwork.

2.1 Knitted Textiles as Flexible Formworks

Knitted textiles have various advantages over conventionally woven fabrics in the definition of complex geometries. Curved spatial surfaces can be created by locally varying the length and width of the textile during production [11]. The mechanical properties of the knitted textile depend on various parameters such as the diameter and material of the used yarn, loop size, tension in the yarn during fabrication or degree of pre-stress in its final state. Those parameters can be continuously varied over the fabric allowing a specifically tailored distribution of properties. Modern CNC knitting machines are able to include straight rovings within the knitted textile (known as inlays), which significantly increase stiffness and introduce a more defined directionality to the fabric. Other features include ribs and channels as shown in Fig. 1. Spacer fabrics are also possible by introducing stiffer materials for the connection between two membranes.

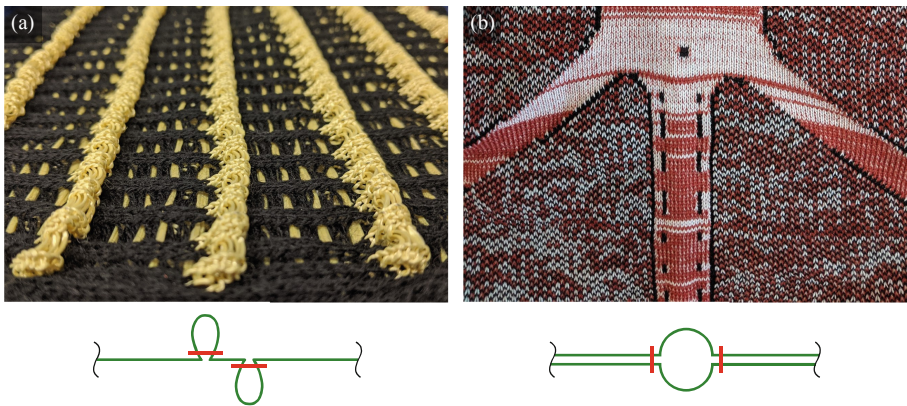


Fig. 1. Weft-knitted textiles with (a) ribs and (b) channels.

The KnitCrete technology developed at ETH Zürich makes use of the knitting features in multiple aspects. Loops or channels within the textile allow the introduction of elements such as bending-active rods [8] or cables [9] that can be used to actively shape the formwork and support the membrane during construction. Therefore, the range of possible geometries extends from the simple full section (Fig. 2a) that is supported from underneath during casting to a variety of new shapes (Fig. 2b–e). Ribbed sections, which significantly reduce the volume and thus, the self-weight while maintaining high stiffness through geometry, can be formed by inflating hollow pockets between two connected knitted membranes (Fig. 3a) or by creating a folded spatial fabric (Fig. 3b).

Variable thicknesses in the shell section can be controlled by implementing sandwich elements with two membranes that are connected by couplers of variable length (Fig. 2c). Openings in the top layer may be used for concrete filling and to let air escape for preventing voids. Furthermore, linear elements such as beams or grid shells

are possible by directly filling concrete into channels within the textile, which (for vertically oriented channels) creates a circular tube section due to the hydrostatic pressure against the formwork (Fig. 2d). Any polygonal shape might be created by introducing cables or bending-active rods defining the vertices of the cross section (Fig. 2e).

Besides integrated support structures, a key aspect in the KnitCrete technology to guarantee form stability during casting and hardening of the concrete is the initial stiffening of the fabric by means of applying a thin layer of high-strength cement paste or a fluid resin (e.g. epoxy). The textile-cement-composite displays a much higher stiffness than the bare textile, which significantly reduces deformations during construction and allows partly straight surfaces.

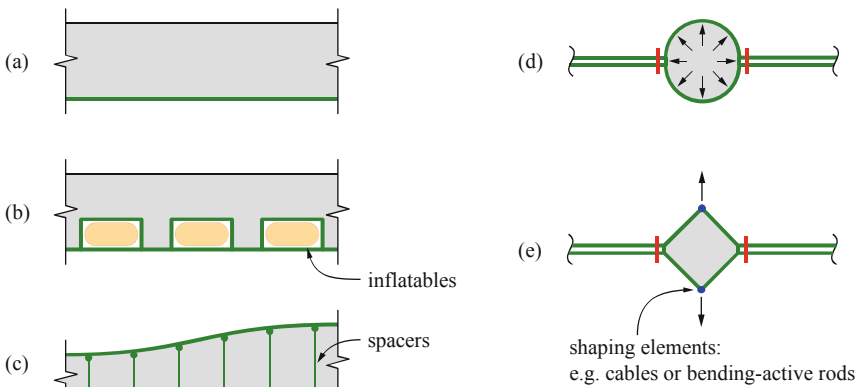


Fig. 2. Schematic overview of possible cross sections with flexible formwork.

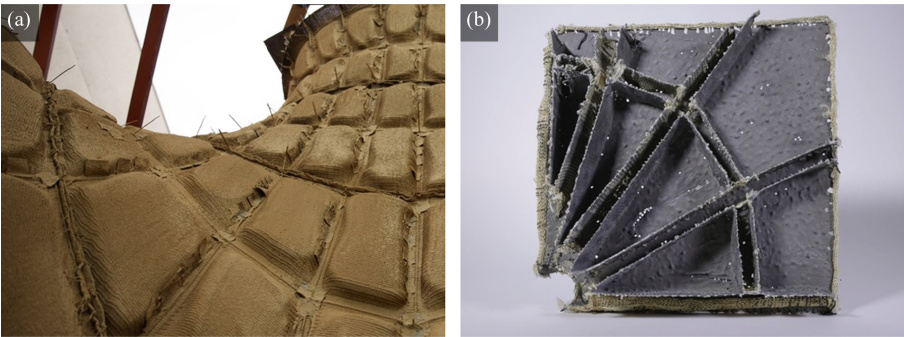


Fig. 3. Ribbed cross sections from (a) inflating hollow pockets and (b) folding.

2.2 Requirements on Reinforcement in Cementitious Composite Materials

Concrete is a quasi-brittle material that displays high compressive strength but very low tensile capacity. It shows a brittle failure mode upon reaching its tensile strength and thus, reinforcement is necessary to ensure an adequate ultimate and serviceability behaviour. Most design approaches rely on the ductility of the material, which (i) allows the redistribution of internal forces to compensate for unknown initial stress states and (ii) prevents brittle failure modes upon reaching the ultimate load. To this end, a ductile reinforcement must be able to resist the cracking load of the concrete.

The most commonly used type of reinforcement in conventional construction are straight reinforcing bars, which are aligned in a bi-directional grid. For standard geometries such as slabs or walls, this reinforcement layout is easy to place on site and its structural performance – in terms of ultimate strength, serviceability and ductility – as well as its workability are unparalleled. However, curved geometries significantly increase the complexity of the reinforcement requiring steel bars to be bent into the right shape and placed at the correct position with little tolerances, which increases manual labour. Furthermore, steel reinforcement demands a minimal concrete cover thickness (usually between 20 and 50 mm depending on structure type and exposition) to guarantee an adequate protection against corrosion, which limits the slenderness of thin shell structures.

2.3 Integrating Reinforcement

Asprone et al. [12] group possible approaches to address reinforcement integration in digitally fabricated concrete either by structural principle – ductile printing material, digitally fabricated composite, compression loaded structures or hybrid solutions – or by the stage of the manufacturing process – before, during and after manufacturing. The present paper mostly revises possible approaches for integrating the reinforcement into the formwork, which classifies as ‘before manufacturing’ and as a ‘digitally fabricated composite’. Moreover, a hybrid solution that uses fibre reinforced concrete for casting the element is studied.

Stay-In-Place Formworks. Flat composite slab systems offer great flexibility where construction needs to be fast and there is only limited space for additional scaffolding (e.g. industrial buildings or bridge decks). During construction, the formwork has enough bearing capacity to carry its self-weight and the load of the wet concrete. After hardening, the formwork acts as bottom reinforcement resisting sagging bending moments. Various material combinations exist, including precast concrete slabs using either short fibres [13] or steel reinforcement [14], corrugated steel sheets [15] or beech-laminated timber [16]. These are mostly suitable for applications with simple geometry due to their high potential for prefabrication of standardised element shapes and sizes. The major challenge is the proper stress transfer at the interface between the stay-in-place formwork and the concrete. The bond stress capacity typically needs to be increased by introducing mechanical shear coupling elements such as embossments in steel sheets, notches in timber plates or dowels, since friction and adhesion alone are not sufficient and thus, delamination would occur.

Textile Reinforced Concrete. By using high-strength fibrous materials for knitted textiles, the formwork can act as a reinforcement in the final state. Textile reinforced concrete (TRC) has gained much interest in academia in recent years. The fibre material ranges from metal, natural fibres such as basalt, synthetic polymers to inorganic materials [17]. The use of non-corrosive materials not only allows the fabrication of much thinner concrete elements since there is no lower limit for the concrete cover to protect the reinforcement, but can also reduce the amount of clinker (required to obtain a high pH-value to passivate steel reinforcement) and thus, decrease CO₂ emissions. Carbon or glass fibre-based textiles are among the most commonly applied materials in practice as they exhibit very high tensile strength (around 3'000–4'000 MPa) and stiffness (glass fibre: ca. 70 GPa, carbon fibre: ca. 240 GPa). However, they tend to be sensitive to lateral loading and exhibit no ductility at all (perfectly brittle materials). Most research and design approaches cover commercially available textile reinforcement by means of bi-directional grids of bundled fibre rovings that are usually impregnated with a resin coating (e.g. epoxy) [18, 19]. Only little literature covers knitted textile reinforcement and no proper mechanical model exists up to date. Due to its dense interlocked structure (Fig. 4a), the tensile capacity of the yarn is reduced. Moreover, many types of fibres are not suitable for direct use as knitting yarn since they often only allow rather large bending radii and thus, would break when knitted. However, as mentioned in Sect. 2.1, it is possible to integrate straight rovings as inlays into the base textile (Fig. 4b). This allows the use of thicker yarns and the fabrication of “quasi-woven” grids of inlays that can follow defined paths (e.g. according to the principal stresses) within the knitted textile.

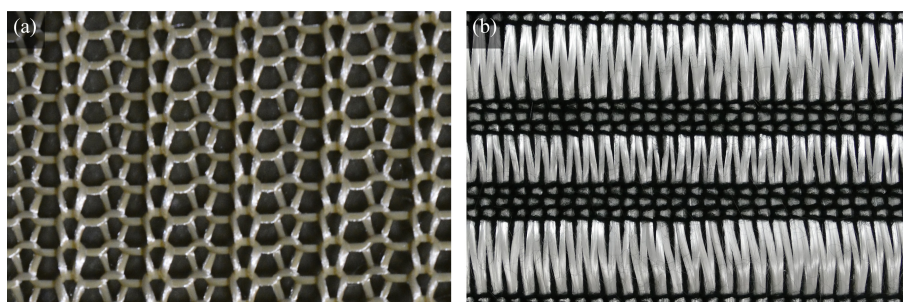


Fig. 4. Flat weft-knitted textile with (a) aramid yarn and (b) glass fibre inlays (white rovings) within base pattern made out of acrylic yarn.

Besides the performance of the reinforcement as a tensile element, its connection to the concrete brings up another major challenge. In conventional reinforcing bars, bond stresses between reinforcing bar and concrete primarily result from mechanical interlock of the profiled bar [20]. Flat sheets of knitted textiles do not have a pronounced surface profile. Furthermore, the cement paste coating creates a cold joint that significantly lowers the bond stress capacity [21]. Ribs in the textile (see Fig. 5) can create a mechanical connection between the reinforcement and the concrete, which leads to enhanced bond conditions and counteracts delamination and spalling.

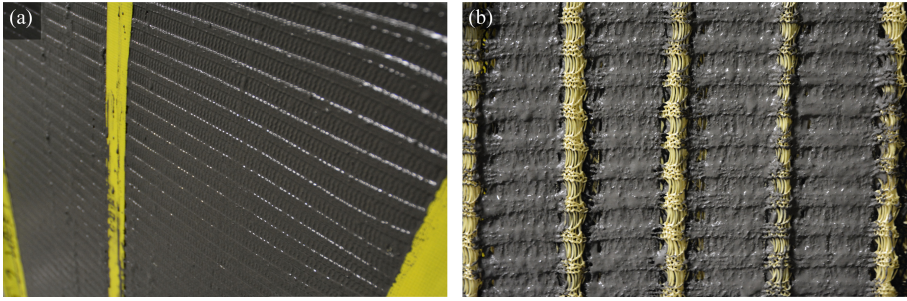


Fig. 5. Knitted textile after application of cement paste coating (fresh state): (a) flat textile; (b) textile with ribs for bond enhancement.

Linear Reinforcement. Placing steel reinforcing bars in spatial doubly curved structures requires more time and, eventually, cost for manual labour due to greater complexity and lesser geometric tolerances compared to simple slabs or walls. However, implementing defined guiding features into the textile can significantly simplify this procedure. Reinforcing bars, cables or sheaths for pre-tensioning tendons (e.g. mono strands) can be threaded through loops or channels and might even act as additional support structure for the flexible formwork as bending-active or hanging elements, minimising temporary support structures during construction. Due to the fixed positions within the textile, there is no need for tedious measuring and arranging work on site. Figure 6 shows two possible concepts for the implementation of linear reinforcement into the textile. The flexible formwork can be suspended from a centred reinforcement layer (Fig. 6a). Alternatively, sandwich elements that consist of two external layers of formwork can carry the reinforcement in the top and bottom faces of the shell section (Fig. 6b). Additional coupling elements between the two layers might be needed to ensure the proper connection of the reinforcement to the concrete and to prevent a breakout of the bars. Such a layout results in very low to no reinforcement covers, which demands the use of non-corrosive materials such as glass fibre reinforcing bars or steel with increased corrosion resistance.

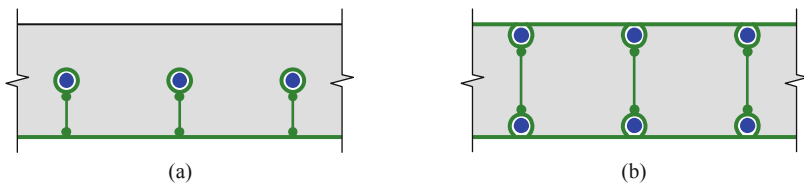


Fig. 6. Concepts for integrating linear reinforcement into knitted formwork: (a) bottom layer suspended from reinforcement and (b) sandwich-elements with top and bottom layer.

Fibre Reinforced Concrete. As a combination or alternative to the previously presented reinforcing approaches, which are installed before concrete placement, fibre reinforced concrete can be used to cast the structural elements in order to improve strength and serviceability. According to Du et al. [22], steel fibres mainly improve the interfacial bonding between textile reinforcement and concrete as well as the shear resistance of textile reinforced concrete specimens, which is especially beneficial for curved structural members as it impedes delamination caused by deviation forces. The influence on the deformation capacity, which might partially compensate for the lack of ductility in the textile material, still needs to be addressed. Existing models for conventionally reinforced concrete members [23] might be adapted for textile reinforcement but more experimental investigations are required.

3 Experimental Investigations

Proper characterisation of the aforementioned reinforcement strategies demands an extensive experimental investigation to assess structural performance and validate the feasibility of critical construction details. The development of a constitutive model for the mechanical behaviour is paramount for implementing stable numerical simulation methods that are required for modelling and designing concrete structures with complex geometries.

So far, the authors' investigations concentrated on the structural testing of weft-knitted textile reinforcement, focusing on (i) various knitting patterns; (ii) fibres (aramid, carbon and glass fibres); (iii) coating type (cement paste and epoxy); and (iv) spatial features to enhance the bond between reinforcement and concrete. The experimental campaign consists of uniaxial tension tests on flat tension ties as well as 4-point-bending beams as shown in Fig. 7.

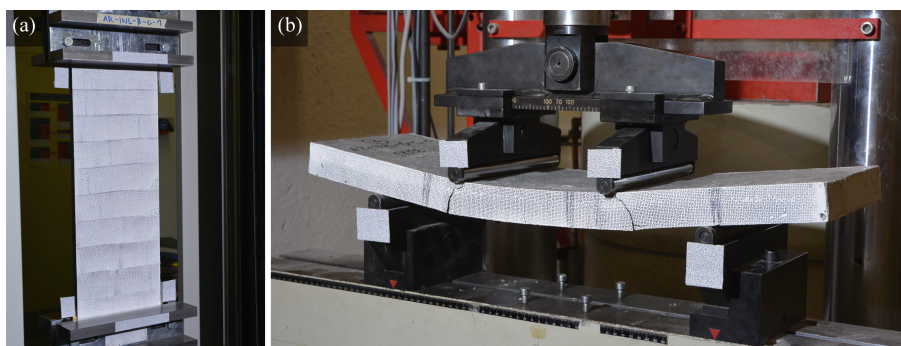


Fig. 7. Textile reinforced concrete specimens (a) in uniaxial tension and (b) in bending.

Preliminary results show that the textile reinforcement considerably increases the post-cracking strength of the concrete although the specimens fail before reaching the nominal ultimate load derived from the textile reinforcement tensile strength and content.

The interaction between reinforcement and concrete results in tension stiffening; the average strains in the reinforcement are lower compared to the bare textile. The Tension Chord Model [24] can be used to describe the load-deformation behaviour. First approaches show a pronounced effect of tension stiffening in the experimental data as shown in Fig. 8, but more test data and analyses – currently in progress – are required to assess the mechanical properties and the interaction between materials to characterise the composite behaviour. Furthermore, the results from the uniaxial tension tests may be used to predict the behaviour of the reinforcement as a tension chord in bending beams.

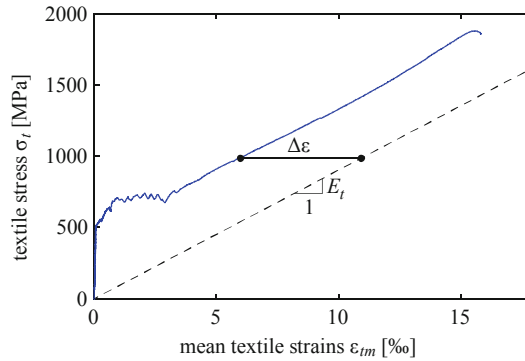


Fig. 8. Load-deformation behaviour of tension ties with textile reinforcement.

The testing scheme for integrated linear reinforcement may follow the same principles and generally, similar experiments may be suitable. Since the bond capacity between the reinforcement and the concrete, considering the low cover thicknesses and potential deviation forces in curved members, is critical for the structural feasibility, the experimental campaign needs to address these challenges with special care and attention.

4 Conclusion

Flexible formworks have shown their potential to significantly increase the efficiency of the fabrication of doubly curved concrete structures by reducing manual labour and material waste. Reinforcement, which ensures structural safety, serviceability and robustness for multiple load cases, is still a major challenge in complex geometries. This paper revised several approaches to integrate reinforcement into weft-knitted textile formwork, decreasing construction time and simplifying construction processes on site.

The use of high-strength fibrous materials for stay-in-place fabric formworks offers the possibility to combine the installation of formwork and reinforcement in a single step. Knitted textiles enable many possibilities to create geometric features without cutting and connecting multiple patches together. Loops and channels within the fabric

can guide linear reinforcement in the form of bars or cables for post-tensioning, which might serve for the erection of the formwork and as support structures during construction. For the proper activation of reinforcement of any kind, the bond conditions at the interface between reinforcement and concrete are the governing parameter, for which mechanical interlock has the biggest influence. Preliminary experimental investigations on concrete tension ties and beams with weft-knitted textile reinforcement show promising results but further research – including large-scale experiments – is needed to validate the feasibility of the proposed reinforcement approaches and identify further challenges for improving structural performance as well as workability during construction.

Current research of the authors focuses on the adaptation and refinement of existing mechanical models to describe the load-deformation behaviour of concrete elements with weft-knitted textile reinforcement and on the further development towards an integral formwork-reinforcement system, considering the potential of linear reinforcement, the addition of short fibres or combinations thereof.

Acknowledgements. The authors gratefully acknowledge Dr. Lex Reiter from the Institute for Building Materials (ETHZ) as well as the students Seraina Buholzer and Salome Geiser for their valuable support during preparation and testing of specimens shown in Sect. 3. This research is supported by the National Centre for Competence in Research in Digital Fabrication, funded by the Swiss National Science Foundation (project number 51NF40-141853).

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Penetration Reinforcing Method for 3D Concrete Printing

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Abstract. Large scale construction 3D Concrete Printing (3DcP) has gained much attention worldwide with the recent developments of many new technologies and proof of concept structures. One inherent limitation in 3DcP is the automatic laying of reinforcement. So far, the methods proposed for integrating vertical reinforcement are rudimentary and involve manual post processes. Majority of 3DcP wall structures overcome this issue by using the printed section as a shell and after hardening involve manual post processes to reinforce the structure. In this paper a new method of reinforcing is introduced termed the Layer Penetration Reinforcing Method (LPRM). This process involves the printing of a predetermined number of layers, then the subsequent penetration of pre-cut reinforcement through the fresh layers. To prove the concept a lab scale wall (300 mm tall) is printed and reinforced with 7 mm deformed steel bar and $\times 9$ mm stainless steel helical bar. The wall is cut into $100 \text{ mm} \times 60 \text{ mm} \times 300 \text{ mm}$ beam sections and tested in 3-point bending with the bar sitting a depth of approximately 70 mm to measure the flexural strength. The samples are compared to conventionally reinforced concrete. Results have shown that the printed beams with deformed bar and helical bar increase the flexural strength of the wall by 184% and 142% respectively. Deformed bar proved superior over helical bar in reinforcing a 3DcP section by obtaining a flexural strength 83% that of a conventional reinforced section, compared to 47% for helical bar.

Keywords: Reinforcing · Vertical walls · Flexural strength · 3D Concrete Printing · Deformed bar · Helical bar

1 Introduction

Large scale construction 3D Concrete Printing (3DcP) is fast becoming the most talked about technology to disrupt the construction industry and potentially revolutionise the way in which we build structures. The process involves the digital controlled and automated robotic deposition of cementitious layers to form the structure [1]. Most commonly the method of deposition is by extrusion, where a stiff cementitious mixture is pumped and squeezed out of a nozzle opening to form the layer [2]. Many researches such as mixture design, rheological mechanics and machine design are dominant areas of focus now. Nonetheless 3DcP has two very particularly challenging issues, namely

weak interlayer bond strength and incorporation of reinforcements. The latter issue is particularly important for 3DcP, to be a truly effective method of construction for building safe concrete load bearing structures since tensile reinforcement must be incorporated.

Many novel efforts have been implemented and explored to tackle this challenge such as post/pre-installed conventional or cable reinforcement, addition of short fibre to the concrete mixture, in-layer direction cable entrainment, concurrent robot arc welding reinforcement and most recently a mesh reinforcing method [3–10]. The problem is that majority of these methods do not address reinforcing vertically through the interlayer (perpendicular to the deposited layer) which is the more critical direction than the layer direction, due to the weakness in the interlayer bond and many wall structures requiring vertical reinforcement. The last two methods mentioned above do address this issue but are still in early or conceptual stages of development, involving very precise automated control and technological development to prevent bottlenecks in the printing process, particularly with arc welding [11].

Majority of large printed structures have overcome this issue by either utilising the printed section as a shell (permanent formwork) with the inner cavity reinforced with rebar and subsequently filled with a flowable concrete, after hardening, or the installation of post-tensioned cables. Nonetheless these methods involve a two-stage process manual process ‘after’ the concrete cures. In this paper we present an ‘in-process’ method where reinforcing is accrued concurrently and autonomously, that is simple to execute the reinforcing across the interlayer.

1.1 Layer Penetration Reinforcing Method (LPRM)

The Layer Penetration Reinforcing Method (LPRM) is conceptualised as a method that involves the printing of a predefined number of layers, then the subsequent penetration of pre-cut reinforcement bars vertically through the fresh layers, then the process is repeated. The automation of this process could be undertaken by a secondary robot or with the printer itself as a secondary attachment. The concept is to insert the bars vertically down, intermittently throughout the printing process. Continuation of this process is maintained until the final build height of the print is achieved (Fig. 1a). There are many unknowns and areas to be explored with this method, such as continuity of bars, lap length/mechanical anchoring, bar size, layer deformation etc. The focus of this paper is to trial the concept and validate the idea in its simplest form with a single bar penetration (Fig. 1b).

Currently, only a few studies have been published on the effectiveness of deformed bar bonded to printed concrete. Initially research by Baz et al. [12] had explored manual printing with a hand extruder over reinforced bar finding promising results for the pull-out strength, comparable to casted variants, except where the bar was penetrated through the layers after printing. It was established that there was a poor bond due to excessive voids/cavities around the reinforcement by the nature of the method was the reason. Other ongoing works by Marchment and Sanjayan [13] looking at the bond profile and its effects from penetration has found similar findings.

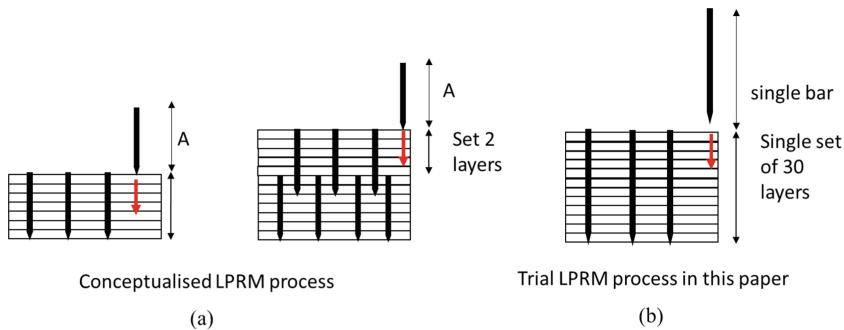


Fig. 1. (a) The process of LPRM where a set of layers is printed, then rebar penetrated into the fresh layers. The second set of layers are printed (shorter height) allowing overlap of the rebar. (b) The process explored in this paper to trial the effectiveness of one bar without overlap.

Although the work of Baz et al. [12] presents solid research findings, it must be noted that the work was not performed with an automated 3D printer, and the rebar was inserted by hand. These two manual tasks performed without provisions for controlled execution, especially the sturdy guided insertion of rebar, will vary results [13]. Nonetheless, the effectiveness of the rebar to work as a flexural reinforcement has not been assessed.

Therefore, the research in this paper aims to explore the feasibility of the LPRM and its effectiveness to work as a vertical flexural reinforcement for walls with loads acting perpendicular to the interlayer. The trialing of two existing reinforcing bar types, namely 7 mm deformed bar and 9 mm stainless steel helical bar, by way of LPRM in a 300 mm tall wall is assessed and compared. For the sake of this experiment the effectiveness single 300 mm bars are used. Beam sections are cut from the wall and tested in 3-point bending. Finally, the samples are compared to conventionally reinforced concrete by calculation.

2 Materials

2.1 Printed Concrete Mix

The material used as the printing feedstock is a ‘fine grained aggregate concrete’ mixture consisting of Ordinary Portland Cement (OPC), silica fume (SF), fly ash (FA), two washed graded sands, tap water and various concrete additives. The two washed graded sands having particle sizes of 500 μm and 840 μm . The additives chosen for the mix include a concrete set retarder (RT), viscosity modifier (VM) and a superplasticiser (SP). The constituents and mix ratios are presented in Table 1.

Table 1. Ratios of the concrete mix constituents

Binder (1)			Sand (1.5)		Tap water 0.3 ^a	Additives g/kg binder		
OPC	SF	FA	500 μm	840 μm		SP	RT	VM
0.8 ^a	0.1 ^a	0.1 ^a	0.5 ^a	1 ^a		2	3	3.4
628.6 ^b	78.6 ^b	78.6 ^b	392.9 ^b	785.7 ^b	235.7 ^b			

Note: ^asignifies values as mass ratios to the binder.

^bsignifies values as kg/m³ of concrete mix.

2.2 Reinforcements

Two primary types of reinforcements were adopted for use in the LPRM nominally 7 mm diameter deformed bar and 9 mm helical wall ties (helical bar) further detailing shown in Fig. 2a. These reinforcements were chosen on the basis of providing ease of insertion into 3DcP layers and provide a strong mechanical bond and provide sufficient cover without bulging the concrete layers. Deformed bar was cut at 300 mm lengths with a 40° point cut for ease of penetration and guidance. The average ultimate tensile strength (UTS) of the deformed bar is 18.9 kN. The 9 mm Helical wall ties are made of 319 type stainless steel making them resistant to corrosion. They are proprietary products commonly used for masonry applications to anchor facades. The twisted fin design allows it to be driven into a predrilled hole cutting into the masonry providing a tight friction bond. This design could prove beneficial for penetrating into fresh 3D printed concrete minimising deforming the concrete layers, whilst also providing a stabilised screwing motion guiding the bar straight. They come in 305 mm pre-cut lengths with an average UTS approx. 17.5 kN.

3 Methods

3.1 Printer and Reinforcement Insertion

The printer used was a 4-axis gantry with a printhead consisting of a conical $\Phi 180$ mm cylinder, $\Phi 40$ mm nozzle and stepper motor-controlled auger. The LPRM is conceptualised to be an automated process with the guided insertion of rebar into fresh printed layers after printing a set amount. Although an automated machine is not yet built, a proof of concept apparatus is used to manually replicate the process. The insertions process is to be displacement controlled. After the desired number of layers are printed a rigid guiding tube was used (Fig. 2b). This guide tube was attached to the gantry print head, so it could be positioned over the layers and rebar could be pushed through to ensure a straight penetration. The tube diameter is 1 mm to 1.5 mm larger than the reinforcement in order to prevent blockage without compromising guiding abilities. It must be noted the deformed bar was *pushed* through while the helical bar was *twisted* through.

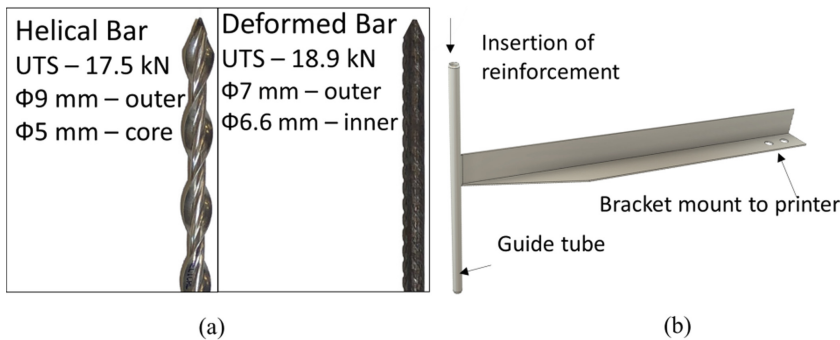


Fig. 2. a) Pictures and specifications of the helical bar and deformed bar reinforcement; b) A schematic of the guide tube that mounts to the printer for the guiding of the reinforcement penetration.

3.2 Printing Samples

A 300 mm (H) $\times$ 450 mm (L) $\times$ 100 mm (W) concrete wall was printed consisting of 30 $\times$ 10 mm thick layers printed side by side. Layers extruded out a Φ 40 mm nozzle at 30 mm/s forming a 50 mm wide layer. After the 30th layer is printed bars are inserted using the guide tube attached to the gantry as described in Sect. 3.1. The total 6 Bars are then inserted at 60 mm ($\pm$ 3 mm) spacings along one side of the wall through the center of the layer as shown in Fig. 3a. A secondary strip consisting of 4 layers was also printed, cut and ground into 6 beams at 40 mm $\times$ 40 mm $\times$ 160 mm for concrete material property testing. All samples were left to cure at ambient temperature (23 ± 3 $^{\circ}$ C, 50% humidity) for 7 days under a plastic sheet.

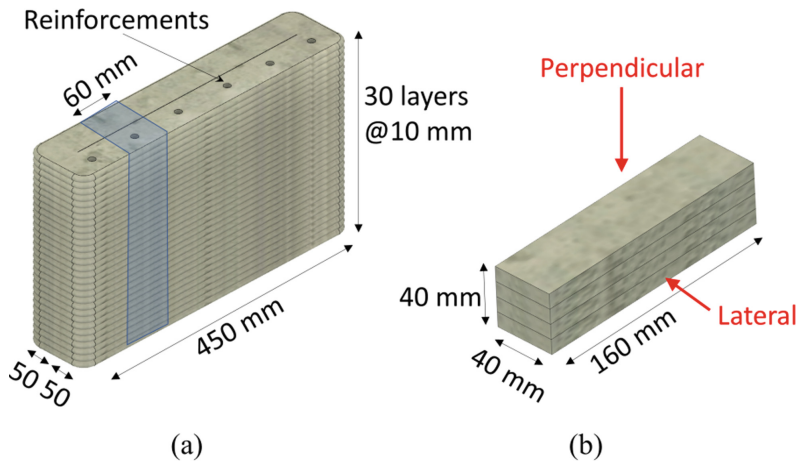


Fig. 3. a) Schematic of the printed wall with reinforcement penetrated, with the highlighted area showing the beam section that are cut from it; b) Schematic of the small, 4-layer beam printed for flexural and compression testing with the testing directions shown.

4 Experimental Procedures

4.1 Concrete Material Properties - Flexural Strength and Compressive of Printed Concrete

Concrete flexural strength was measured, by using the 3-point bending test rig and procedures stated in BS EN 196 1:1995 [14]. Printed beams ($40 \text{ mm} \times 40 \text{ mm} \times 160 \text{ mm}$) were tested at a span of 100 mm under a load rate of 15 MPa/s. Three samples were tested being loaded perpendicular to the printed layers, while the other 3 were loaded laterally to the printed layers (Fig. 3b).

Compressive strength was tested using the test rig and procedure stipulated in BS EN 196 1:1995 [14]. This standard allows the fractured halves obtained from the flexural testing in previously mentioned, to be used. The halves are placed between two $40 \text{ mm} \times 40 \text{ mm}$ platens and compressed at a load rate of 33 MPa/s. A total of 6 samples were tested in each layer direction, namely perpendicular and lateral.

4.2 Flexural Strength of Reinforced Samples

After 7 days the printed wall was cut and ground into 6 approx. $60 \text{ mm (b)} \times 100 \text{ mm (D)} \times 300 \text{ mm (L)}$ beam sections to test in 3-point bending (Fig. 3a). A span of 280 mm at a displacement rate of 0.5 mm/min was used. The samples are orientated so that the reinforcement is at the bottom approx. 70 mm from the top (d) (Fig. 4).

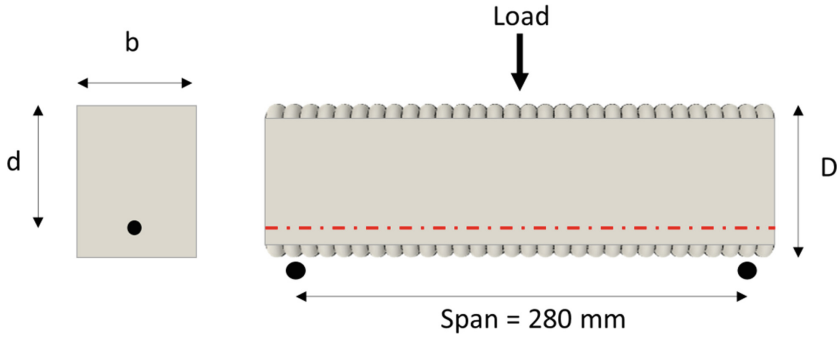


Fig. 4. 3-Point bending test set up with printed reinforced section.

Calculated Moment Strength. The approximate moment strength ($M_{ult.cal}$) is calculated using Eq. (1). Where the ultimate tensile force of the reinforcement ($F_{u.bar}$) and the number of bars (N_{bar}) are multiplied by the internal lever arm. The internal lever arm is taken as an approximate 90% of the depth to reinforcement (d).

$$M_{ult.cal} = F_{u.bar} \times N_{bar} \times 0.9(d) \quad (1)$$

Flexural Bond Strength. The modulus of rupture which is analogous to an unreinforced flexural strength and bond strength ($f'_{t,bond}$) of the interlayers is calculated by Eq. (2). Where (M_{cr}) is the moment that initial cracking occurs and obtained from the results, ($D/2$) is the internal lever arm which is half the depth of the section and (I_g) being the sections gross second moment of inertia.

$$f'_{t,bond} = (M_{cr} \times D/2) / (I_g) \tag{2}$$

5 Results and Discussions

5.1 Concrete Material Properties - Flexural Strength and Compressive of Printed Concrete

The test results for the flexural strength specimens are plotted in Fig. 5a. Samples tested perpendicularly display an average flexural strength of 6.12 MPa, while the lateral samples display an average flexural strength of 5.63 MPa. As both sample sizes display error within the bounds of each other with only a difference of 8% between averages it can be concluded that there is minimal if any anisotropic effect noticed.

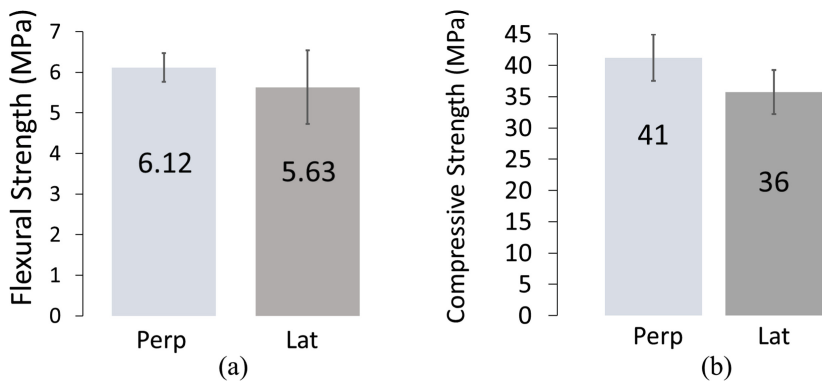


Fig. 5. a) Flexural strength results of the concrete, b) compressive strength results of the concrete

Compressive strength test results for the fractured halves of the specimens tested in Sect. 5.1 are shown in Fig. 5b. Samples tested perpendicularly obtained an average compressive strength of 41 MPa, while lateral samples obtained a slightly 13% lower strength of 36 MPa. Similarly, the error, like witnessed in the flexural testing, is within the bounds of each other, therefore only minimal if any anisotropic effect can be considered.

5.2 Flexural Strength of Reinforced Samples

Results for the 3-point bending tests of the deformed bar (D) and helical bar (H) samples are plotted in Fig. 6 and tabulated in Table 2. Deformed bar samples (D1, D2, D3) display initial cracking moments (M_{cr}) between 499 and 547×10^3 Nmm. After cracking is initiated the reinforcement is engaged where the samples reach an ultimate moment strength (M_{ult}) between 930 and 1041×10^3 Nmm, increasing the flexural strength by 184%. Sample D1 and D3 show sudden brittle failure displayed by the sharp drop in strength after M_{ult} is reached. Sample D2 is similar although there are two short sudden drops in strength before a slightly slower failure occurs. Undoubtedly this indicates that the slippage of the reinforcement is occurring.

Table 2. Sample dimensions and 3-Point bending test results

Sample	b (mm)	D (mm)	d (mm)	$f'_{L,bond}$ (MPa)	M_{cr} ($\times 10^3$ Nmm)	M_{ult} ($\times 10^3$ Nmm)	$M_{ult,Cal}$ ($\times 10^3$ Nmm)
D1	60	96	68	5.41	499	985	1190
D2	64	92	72	6.16	556	930	
D3	63	98	73	5.42	547	1041	
H1	56	91	67	5.18	400	508	1102
H2	50	100	71	4.14	345	521	
H3	53	95	70	4.28	341	514	

Helical bar samples (H1, H2, H3) display M_{cr} between 341 – 400×10^3 Nmm, then reaching an M_{ult} between 508 and 521×10^3 Nmm, increasing moment strength by 142%. Unlike the deformed bar samples, the failure mechanism is less sudden/brittle, but more of a progressive slip. As can be seen from in Fig. 6 from approx. a strength between 450 and 400×10^3 Nmm is maintained after M_{ult} is achieved. This is most

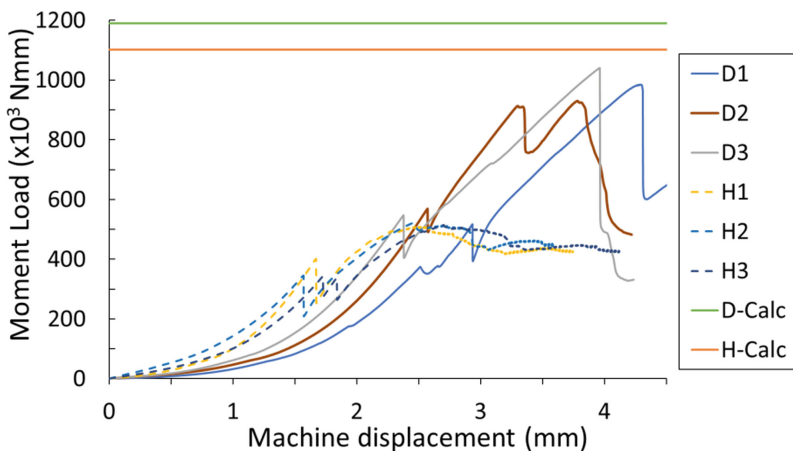


Fig. 6. Flexural strength results of the reinforced 3DcP samples

likely a result of the twisted fins slipping and creating a counter rotation on the bar as there is no torsional restraint.

Calculated Moment Strength. The $M_{ult,cal}$ values are plotted as straight lines in Fig. 6 for deformed bar and helical bar noted as D-Calc and H-Calc at 1190×10^3 Nmm and 1102×10^3 Nmm respectively. Comparing these values to the actual M_{ult} , both samples fall short, but this is not to say that their performance is poor. The average M_{ult} of the deformed bar achieves approx. 83% moment strength of a calculated conventional reinforced section, whereas the helical bar achieves only approx. 47%. As reiterated throughout, slippage of reinforcement being the main contributing mechanism of failure. A photo of the samples cracking is shown in Fig. 7a. Regarding the lower flexural strength of the helical reinforcement, it is hypothesised that concrete coverage of the bar and formation of voids/cavies due to its twisted nature, creates a sub optimal bond compared to that of deformed bar. Obviously, it is noted deformed bar has similar bond problems, but at a far lesser extent as the ribs of the deformed bar increase mechanical friction [12, 13]. A comparison of the concrete to steel bond is shown in Fig. 7b.

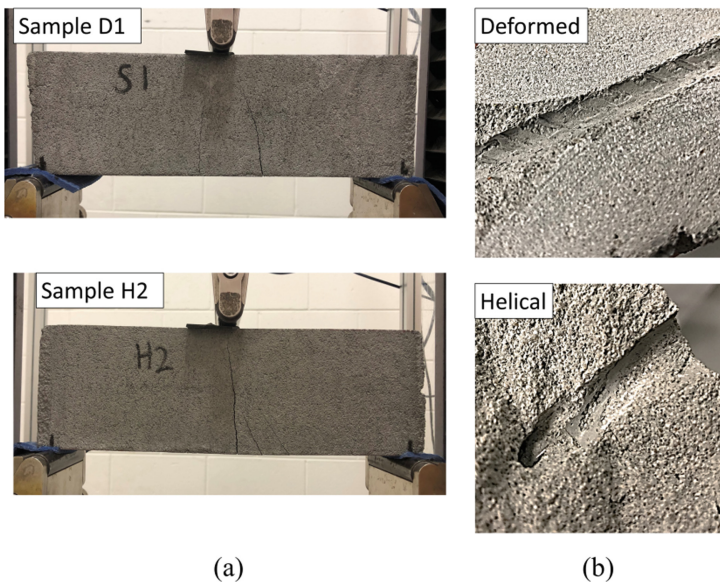


Fig. 7. a) Sample D1 and H2 in the 3-Point bending test showing flexural cracking; b) A close-up picture of the bond impressions left in the printed concrete beams showing the deformed bar with a much better bond area than that of the helical bar.

Flexural Bond Strength. A comparison of M_{cr} between the deformed bar and helical bar samples shows a noticeable difference although should be justified by the slight geometrical differences. Helical bar samples (by coincidence) have slightly smaller dimensions and thus cracking will occur earlier compared to the deformed bar samples. Observing the results for $f'_{t,bond}$ in Table 2, deformed bar samples again express higher

bond strengths (5.41 MPa – 6.16 MPa). Comparing the helical bar samples, they range slightly lower (4.14 MPa – 5.18 MPa). The range in which these results occur are slightly large margin of error although, this is not unusual for bond testing as many processing parameters effect the sample and test results. Another explanation could be the positioning bars H2 and H3 where placed on the outter most points on the wall. As more of the interlayer is exposed to the environment, influences such as drying shrinkage and moisture absorption effect interlayer bond strength [15–19].

6 Conclusions

The Layer Penetration Reinforcing Method (LPRM) aimed at providing a simple ‘in-process’ vertical reinforcing method for 3DcP structures. This method focuses on the use of penetrating reinforcing bars through printed layers during their fresh state. The use and effectiveness of deformed bar and helical bar in this process is unknown, and thus explored whilst comparing the performance of a conventionally reinforced concrete section. A 3DcP wall section reinforced with deformed bar and helical bar is cut into smaller beam sections and tested in 3-point bending to measure flexural strength. The following conclusions were found:

1. Both deformed bar and helical bar were successfully used to reinforce a 3DcP section by increasing moment strength by 184% and 142% respectively compared to the cracking moment strength.
2. Deformed bar was superior to helical bar in reinforcing a 3DcP section by obtaining a moment strength 83% that of a conventional reinforced section, compared to 47% for helical bar.
3. The failure mechanism for all samples was slippage of the reinforcements.

The work in this study proves that the LPRM in conjunction with conventional reinforcements can be used effectively to reinforce 3DcP elements. This is a major success in transitioning current technologies into this new field. Currently the process of LPRM is manual, but with these findings, the concept is consolidated and lays foundation to effectively building an automated system. Further advancements and research will be undertaken on larger scale specimens and investigate methods of providing continuity with the reinforcement at longer lengths/spans and ways to enhance the bond.

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Combining Multiple Loads in a Topology Optimization Framework for Digitally Fabricated Concrete Structures

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Abstract. In recent literature, topology optimization gathered growing interests given its interplays with digital fabrication and additive manufacturing technologies. Notably, the topological optimization of concrete-like elements requires the study of stress-constrained optimization problems due to strength anisotropy, whose solution presents more challenges with respect to classical stiffness-to-weight maximization. For the purpose of fostering the use of topology optimization techniques in real-application scenarios, in this work we present an iterative algorithm to design lightweight structural concrete elements in presence of multiple load actions, and under the restriction of anisotropic stress-constraints. More specifically, our framework is based on the combined use of a proportional material distribution scheme and a Risk-Factor paradigm, to design performative solutions while limiting the failure probability of the structural element. To validate our approach, we define a parametric set of actions which combine bending and axial load, as commonly utilized in a structural engineering framework. In our computational experiments, we assess the robustness of our method and study the relationships connecting load parameters with the resulting solution properties.

Keywords: Topology optimization · Concrete structures · Combined load

1 Introduction

Recent advancements in Digital Fabrication (DF) and Additive Manufacturing (AM) represented a significant technological breakthrough, allowing the production of irregular and complex designs that were either unfeasible or not affordable for traditional production paradigms. This scientific evolution found a close synergy with the development of Topology Optimization, whose aim consists in the optimization of shape and connectivity of a structure [2, 12]. The resulting intertwining of innovative manufacturing processes and optimization procedures is attracting increasing interests in scientific literature, with the aim of automatically designing and building structural elements characterized by optimized performances [14].

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F. P. Bos et al. (Eds.): DC 2020, RILEM Bookseries 28, pp. 691–700, 2020.

https://doi.org/10.1007/978-3-030-49916-7_69

This research stream has led to innovative solutions in a wide variety of application fields, such as: aerospace engineering [15], nano-photonics [6], and in the design of patient-specific implants [13].

In civil engineering, particularly focusing on the study of cementitious materials, topology optimization methods are still far from achieving a full integration in the design-to-production streamline of concrete elements. Several challenges have still to be overcome to bridge the gaps separating design and production, if we compare the technological maturity achieved for example in the processing of polymers.

Primarily, the challenges faced in the design-optimization phase are related to safety requirements of the structures to be optimized. In fact, to properly take into account risks of failure and collapse, the optimization problem of interest has to necessarily be formulated as a stress-constrained problem [8], rather than adopting the classical stiffness maximization (equivalently compliance minimization) model. However, stress-constrained topology optimization bears more demanding mathematical challenges such as a possibly high number of local constraints, and non-linearity [9].

Moreover, additional issues are related to the strength anisotropy of cementitious materials. The different magnitude of tensile and compressive strengths that characterizes concrete makes the classical Von-Mises criterion unsuitable for the proper formulation of stress constraints. Starting from this assumption, in [10] a novel formulation of stress-constraints is proposed, that is able to asymmetrically control tensile and compressive limits of concrete.

Additionally, to properly evaluate the capabilities of topology optimization in the design of feasible concrete elements, further experiments are required to address more complex loading scenarios, possibly characterized by a set of multiple simultaneous actions. The aim of this work consists in the exploration of topology optimized design of concrete elements subjected to combined axial and flexural load, as a frequent in-service condition in concrete structures.

2 Mathematical Model and Methodology

The aim of topology optimization consists in looking for the optimal shape and connectivity of a physical domain to achieve the best structural performances of a solid element.

Commonly, given an objective function and a set of constraints, a problem instance is in general conveyed through: a domain Ω , boundary conditions bc , loads F , and a set of material properties.

According to usual practices, a topology optimization algorithm is made up by two synergetic ingredients: a finite element (FE) model – to solve the mechanical problem of interest –, and an optimization procedure.

For the sake of simplicity, in the following the optimization of a 2D domain is considered. To model the problem, the *density-based approach* introduces a FE mesh M and decision variables $x_e \forall e \in M$, with $0 \leq x_e \leq 1$ (see Fig. 1). Practically speaking, the elements of the mesh are mechanically activated in

correspondence of the decision variables x_e , meaning that a value closer to 1 lets the element contribute to the global stiffness matrix, while a value is close indicates that the behavior of the element is close to be unresponsive.

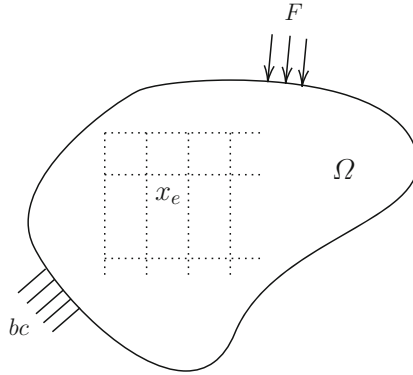


Fig. 1. Generic representation of a topology optimization scenario.

Accordingly, as done in [10], the stress-constrained problem can be formulated as

$$\min \frac{\sum_{e=1}^N x_e}{N} \quad (1)$$

s.t.

$$\mathbf{K}\mathbf{u} = \mathbf{f} \quad (2)$$

$$RF_i^e \leq p \quad \forall e, i = 1, 2, p \in (0, 1] \quad (3)$$

$$\mathbf{x} \in [0, 1]^N, \quad (4)$$

where the objective function – also referred to as *average density* – (1) minimizes the total material of the domain Ω ; $\mathbf{K}$, $\mathbf{u}$, and $\mathbf{f}$ are the global stiffness matrix, the global displacement and force vectors, respectively. Finally, the stress constraints (3) are expressed in terms of the two *risk factors*, defined for each principal stress direction, as:

$$\begin{cases} RF_1^e = \max \left(\frac{\sigma_1^e}{\sigma_+}, \frac{\sigma_1^e}{\sigma_-} \right); \\ RF_2^e = \max \left(\frac{\sigma_2^e}{\sigma_+}, \frac{\sigma_2^e}{\sigma_-} \right); \end{cases} \quad \forall e. \quad (5)$$

where σ_1^e e σ_2^e denote the two principal stresses of e in the x and y principal directions, respectively, and σ_+ and σ_- represent the characteristic tensile and compressive strength of the material. Lastly, p is a safety factor introduced to control how close the stresses measured in the optimized beam can be to the characteristic stress limits σ_+ and σ_- .

The optimization procedure proposed in [10] to handle risk-factors – and thus anisotropic strength requirements – is an iterative algorithm named Ps_TO, and based on the procedure described in [3].

In particular, after a first initialization phase, a starting solution is built by filling each element of the FE mesh with a constant amount of material, $x_{st} \in [0, 1]$, and a FE analysis is carried out to compute the stresses in the designed solution. Each iteration of the algorithm is the coupling of two phases: a solution update procedure and a stress computation. The latter phase evaluates the structural performances and the feasibility of the temporary solution, while the former uses these information as a feedback to adjust the total amount of material distributed in the physical body.

If the FE computations reveal that some points of the structure are overstressed, i.e. that $RF_i^e > 1$ for some e , then some material is added to the domain, otherwise, a lighter structure can be obtained by removing material.

The new amount of material is distributed proportionally among the elements of the mesh, in a way that elements with higher Risk Factors – and thus stress values closer to the characteristic limits – are filled with more material.

As last step of each iteration, the optimization procedure checks the stopping criteria. The algorithm terminates whenever: (i) a minimum number of iterations has been performed, and (ii) the maximum of all the risk factor RF_i^e among all elements is close to 1 (i.e. within a user-defined tolerance). The aim of the first condition is to avoid the convergence to poor quality solutions encountered in the first steps of the iterative process, while the second condition is founded on the hypothesis that lightest structures are most likely obtained once it is no longer possible to subtract any amount of material due to the stress limitations.

At the end of the iterative process, the Ps_TO returns as output the best feasible solution found in the search process, i.e. the lightest solution whose principal stress tensors respect in any element $e \in M$ constraints (3).

3 Numerical Experiments

The numerical experiments investigated in the present work aim at evaluating the solutions designed by the Ps_TO algorithm in the optimization of structural elements under combined load configurations.

To this aim, the case analyzed consists in a 3-meters-long concrete cantilever, with a square cross-section ($0.4 \times 0.4 \text{ m}^2$), upon which a combination of a uniformly distributed (in the cross section) axial load (C) and a flexural action (P) acts. In these analyses the concrete is assumed to belong to strength class C20/25 [1]. The physical dimensions and the loading condition of the cantilever are shown in Fig. 2, while Table 1 summarizes the stiffness and tensile (σ_+) and compressive (σ_-) strengths of class C20/25.

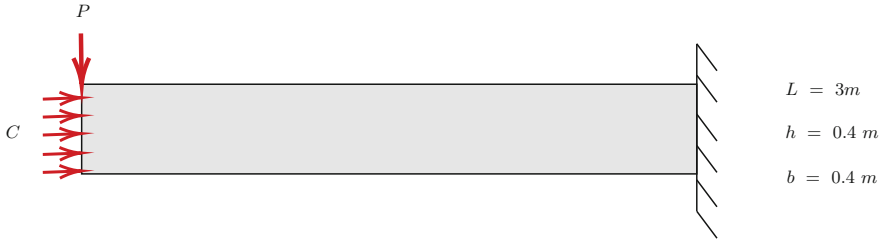


Fig. 2. Representation of loads and boundary conditions.

Table 1. Material properties characterizing strength class C20/25 [1].

Class	E (GPa)	σ_- (MPa)	σ_+ (MPa)
C20/25	30	-20	2.2

The axial compressive stress levels adopted in the numerical experiments are obtained considering a percentage of the characteristic compressive strength σ_- , obtained through the reduction factor ρ . The corresponding axial force is then obtained by:

$$C = \rho \cdot |\sigma_-| h b, \quad (6)$$

In order to design a realistic loading configuration, and to ensure an axial load that allows for material subtraction in the domain Ω , the value selected for ρ in the numerical experiments is either 0.1 or 0.2, accounting for a total 10% or 20% of $|\sigma_-|$. Starting from C and considering the combination with the flexural load, the magnitude of P is derived by imposing two separate target values for the eccentricity a associated to the position of the resulting load in the cross section:

$$a = \frac{P L}{C} \quad \Rightarrow \quad P = \frac{a C}{L}. \quad (7)$$

In particular, the two investigated values for a are, respectively, $h/6$ and $h/12$, see Fig. 3.

Both values correspond to a fully compressed cross section with minimum stress equal to zero in case of $a = h/6$ or higher in case of $a = h/12$, as represented in the figure with respect to the kernel dimensions.

The resulting combinations of distributed axial load and flexural forces are grouped in four distinct cases to be analyzed – cases: 1a, 1b, 2a, and 2b –, summarized in Table 2.

The cantilever designs are shown in Figs. 4 and 5, while for each solution Table 3 summarizes the average density, the maximum compression ($\bar{\sigma}_-$) and traction ($\bar{\sigma}_+$) measured in the cantilever, and the maximum vertical displacement ($\max U$).

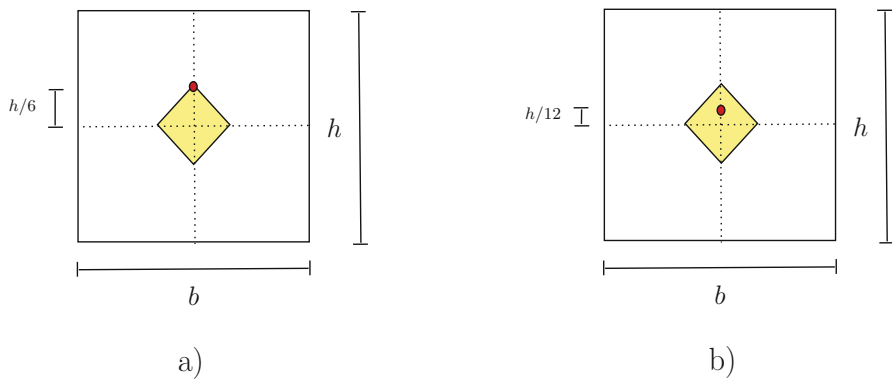


Fig. 3. Eccentricity values considered in the numerical analysis.

Table 2. Summary of cases analyzed in the numerical experiments. The values $\rho |\sigma_-|$ correspond to the full beam section.

Case	$\rho \cdot \sigma_- $ [MPa]	C [kN]	P [kN]	a [mm]
1a	2.0	320	7.11	66,67
2a	2.0	320	3.56	33,33
1b	4.0	640	14.22	66,67
2b	4.0	640	7.11	33,33

The material distributions that characterize the cantilevers evidence a pronounced dendriform branching structure. This topology is well known in structural engineering and architecture, and has been extensively studied for its mechanical stability [4,5,11].

Moreover, the results reported in Table 3 evidence that the Ps_TO converged for all the analyzed cases, and that the material distribution is influenced, mainly, by the effect of the axial load C . In fact, the average densities of cases 1a and 2a – $\approx 40\%$ – appear significantly smaller than those achieved in the optimization of cases 1b and 2b – $\approx 70\%$ –, for which the load C is doubled. Conversely, comparing the solutions for 1a and 2a – or equivalently 1b and 2b – it is possible to note that the magnitude variations of P do not determine significant changes in the topology. This feature is due to the nature of the load configurations considered, indeed, the algorithm converges to solutions closer to the full beam in order to distribute a higher axial load on a wider cross-section.

Coherently with the numerical experiment described in [10], the maximum values of compressive stress $\bar{\sigma}_-$ measured in the optimized cantilevers are significantly smaller than the material characteristic limit, while the more restrictive tensile stress limit σ_+ is almost always attained by $\bar{\sigma}_+$. While this could represent a concerning feature in the implementation of optimized elements in a real structure, an adequate safety level can be reached setting smaller value for p in constraints (3).

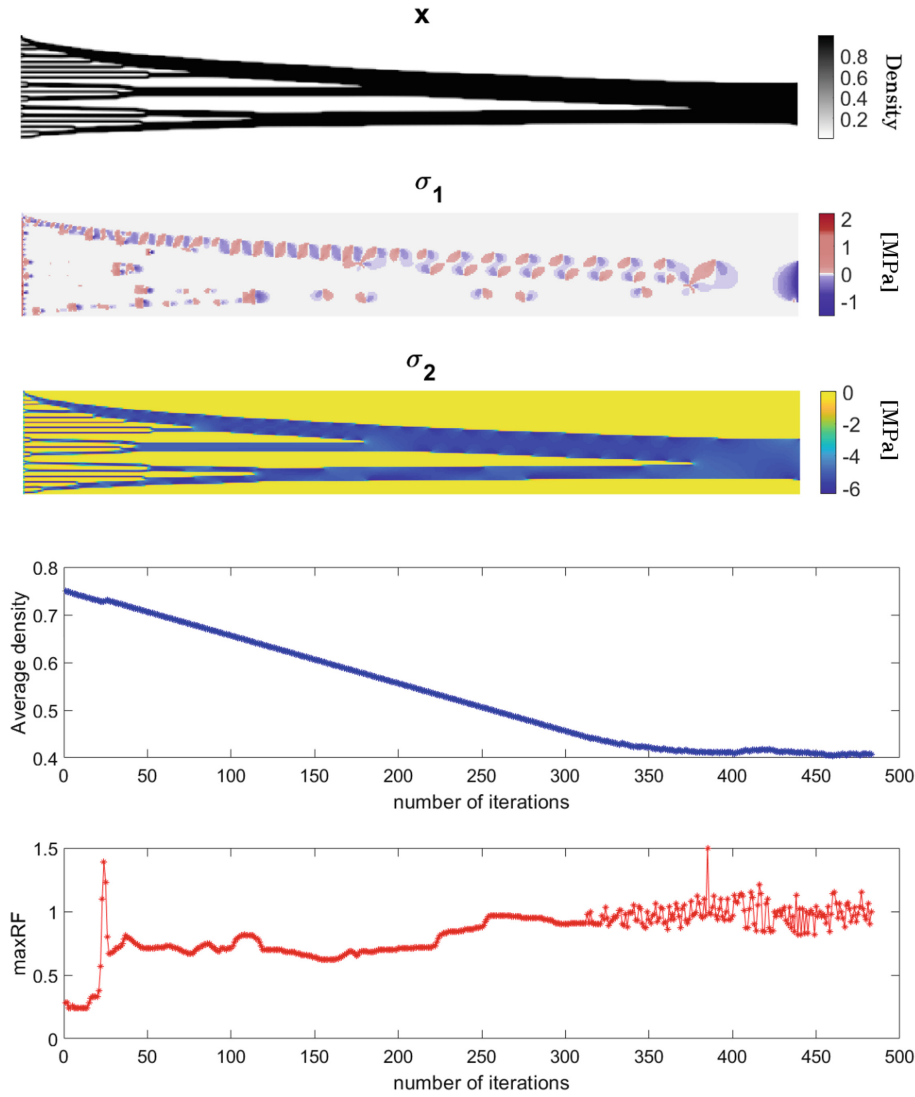


Fig. 4. Optimized solution for case 1a: design, stress distributions, and iteration summary.

Finally, observing the plots of Fig. 4 that shows the evolutions of the Average density and the maximum Risk Factor, it can be noted how the algorithm converged to solutions with a 40% average density around iteration number 350. Simultaneously, the maximum Risk Factor value encountered instability phenomena, locally passing the allowed value of 1. This behavior is related to the

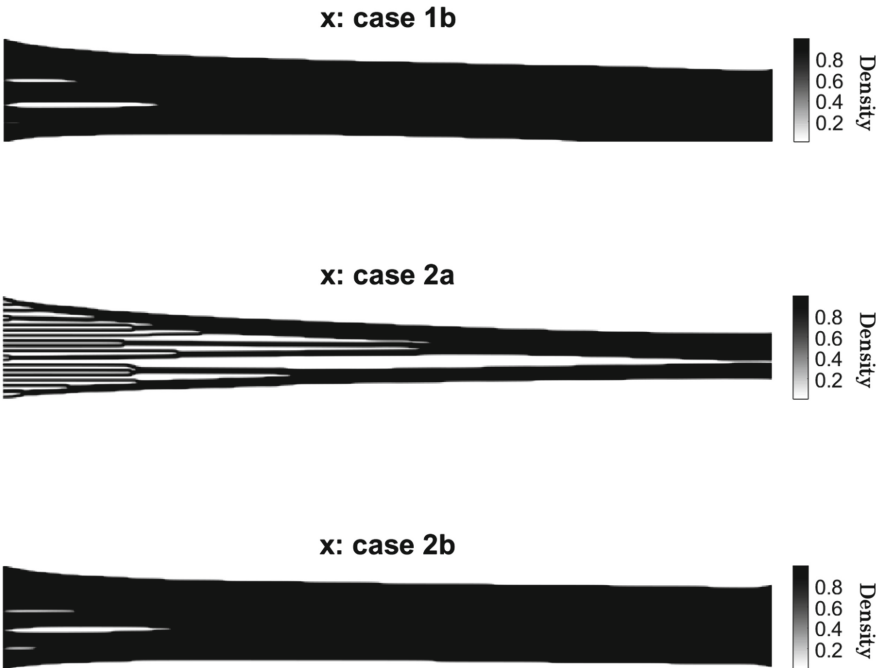


Fig. 5. Optimized design cases 1a, 2a, and 2b.

Table 3. Characteristics of optimized solutions obtained for cases 1a-2b.

Case	Avg density (%)	$\bar{\sigma}_-$ [MPa]	$\bar{\sigma}_+$ [MPa]	$\max U$ [mm]
1a	40	−6.394	2.200	0.58
2a	42	−6.276	2.200	0.62
1b	72	−9.425	2.200	0.56
2b	73	−7.000	2.13	0.54

heuristic observation that the lightest structures are most likely obtained once it is no longer possible to subtract any amount of material due to the stress limitation, i.e. when the stresses are close to the characteristic limit of the material.

4 Conclusions

This paper investigated the optimization of concrete cantilevers under the combined action of a distributed axial load and a flexural load. In particular, the explored configurations were designed to obtain two distinct eccentricity values, related to a fully compressed cross section with minimum stress either equal to zero, or higher.

In particular, the optimization procedure – named Ps.TO – achieved solutions characterized by dendriform branching topologies. For each of the four cases considered, the stress limits enforced were properly respected, and the material amount distributed accordingly.

However, to foster a proper integration of topology optimization algorithms in the conceptual design of concrete elements, several issues have yet to be overcome. While the optimization procedures are evidencing increasing flexibility in the solution of more complex boundary conditions and load configurations, a study on the inclusion of reinforcing steel in the optimized solution is necessary to design structural elements that can be widely employed in realistic scenarios.

Moreover, to avoid post-processing procedures that could possibly affect feasibility and local optimality [7], the mathematical formulation of the design problem has to necessarily include case-specific constraints to obtain feasible solutions for a given printing technology. For example, different printing processes may demand minimum or maximum sizes of the pattern defining the topology, or a predefined shape required by the printing nozzle. Analogously, to obtain workable designs for a printing robotic arms, the paths that define solutions have to be continuously traceable, thus suggesting the inclusion of additional constraints.

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Potential for the Integration of Continuous Fiber-Based Reinforcements in Digital Concrete Production

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Abstract. While digital concrete production is a highly promising and vibrant research topic regarding an increase of the degree of automation in the construction industry, some critical questions remain unanswered. One of these challenging questions concerns the integration of reinforcement into the production process. In this paper, the authors present continuous fiber-based materials as a viable and promising alternative reinforcing material for the integration in digital concrete production. To this end, current approaches for the integration of reinforcement into digital concrete production are summarized. The production process of different continuous fiber-based materials is described and their application in textile reinforced concrete is explained. The authors also evaluate the feasibility of one specific approach to the integration of textiles into the digital concrete production process.

Keywords: Digital fabrication · Concrete reinforcement · Textile reinforced concrete · Fiber-based materials

1 Introduction

In addition to increasing the productivity across many industries, the advent of digitalization and automation has enabled the introduction of digital fabrication. Digital fabrication, also termed “the fourth industrial revolution”, offers the production of fully customized, complex products at low costs and in small batches. This is of high interest in the construction industry, where highly complex, unique structures are often desired by architects and clients.

Concrete, being the second most used material in the world after water [1] and dominating current structural construction, is of the highest priority when adapting digital fabrication methods for use in the construction industry. Digital design and planning are comparatively well developed in the construction sector (e.g. CAD and BIM), but the means of digitalized concrete production are comparatively lesser developed [2]. However, research and development in this field has been accelerating over the recent years and first commercial products and buildings resulting from the use of such approaches are now available. However, there exists a need to further the research required to develop practicable solutions for the complex requirements present in the construction industry.

One of the central questions, in research on digital concrete fabrication today, concerns the integration of reinforcement into the printed structure [1–3]. Many current concrete printing projects do not utilize any reinforcement, which severely limits their applications. Most of the projects utilizing reinforcement use steel based reinforcements or short fibers added to the concrete matrix. In this paper, the authors present another possible reinforcement material: continuous fiber-based reinforcements, or, textiles.

2 Current State of the Art: Integration of Reinforcement into Printed Concrete Structures

Existing approaches for the integration of reinforcement into the 3D-printed concrete structures can be divided based on various criteria. One important criterion is the manufacturing mode of the reinforcement, i.e. whether the reinforcing material itself is produced using digital fabrication processes or using traditional fabrication processes. Another criterion is the integration moment of the reinforcement, i.e. whether the reinforcement is placed prior, during or after the concrete printing process. The last distinguishing criterion relevant to this paper is the reinforcement type. Approaches differ in the material (e.g. steel or polymers) and design (e.g. mesh or bars) of reinforcements. Some approaches are presented below, although this list is by no means exhaustive.

2.1 Digitally Fabricated Reinforcement

Some projects aim to combine the digital concrete production with the digital production of the reinforcement. One example of this is the project Mesh Mould, in which a reinforcing cage made of polymer or steel is placed using an industrial robot. While the polymer mesh is printed by melting the polymer and extruding it using a specifically developed effector, the steel mesh is produced by processing pre-fabricated steel wires and shaping them using another specifically developed effector. After completion, the mesh is filled in with concrete [4].

Another example is the 3D-printing of steel bars for as reinforcements using gas-metal arc welding. In this approach, steel bars are printed through deposition of material in small layers, which also allow for a variation in thickness along the length of the bars [2].

A third example involves the use of continuous carbon fibers impregnated with fine grained minerals. After impregnation, these fibers are arranged in a mesh according to the required geometry of the component. The mesh can be used for traditional concrete production methods, such as casting, as well as for digitally produced concrete [5].

2.2 Temporal Based Reinforcement Integration Techniques into the Process Chain

Placing the Reinforcement Prior to Digital Concrete Production: In this approach, the reinforcement is fixed in place and concrete via a digitally controlled deposition process i.e. material is added in layer by layer. One form of this approach is used by HunagShang Tengda Ltd., China who first erected the frame, rebar support and utilities of a house and added concrete using a 3D printer with a specifically designed forked printing head capable of adding concrete from both sides of the reinforcement [2, 6].

An alternative form to this approach uses ‘Shotcrete’. Using a process called Shotcrete 3D Printing (SC3DP), columns are produced by spraying shotcrete on pre-placed longitudinal and stirrup reinforcement [7].

Placing the Reinforcement During Digital Concrete Production: In this approach, the reinforcement is placed at the same time as the concrete layers. One example of this approach is the reinforcement entrainment device (RED), which allows for the addition of steel cables or chains into the layers of concrete as they are printed [8]. A further example is developed in the research project ‘Freeform.Zem.Text. Bau’. This approach uses narrow textiles made of glass fibers which are placed in between the layers during the concrete printing process [9]. Both approaches, however, have limitations in their available directions of the reinforcement, since only reinforcement in the direction of printing is possible. Thus these processes are spatially constrained which is a primary requirement when complex building structures are to be produced. Hence, currently in such cases, a fallback on traditional construction techniques occurs.

Another approach in this category is the inclusion of short fibers as dispersed reinforcement in the concrete matrix. Short fibers made of steel, glass or polymers are widely used in the construction industry, and their addition to digital concrete fabrication began early in the development of the process. However, while short fibers offer some reinforcement, they are not able to fully replace continuous reinforcement for most cases, due to limited load bearing capabilities.

Placing the Reinforcement After Digital Concrete Production: In this approach, the reinforcement is placed after the digital concrete fabrication is completed. One example of such a technique is the production of integrated formworks via digital concrete production. Reinforcement is then placed in the integrated formwork, which is then filled in with concrete [10].

Another alternative is the placement of reinforcing materials onto the surface of the printed concrete, usually covering the reinforcement by spraying/placing another layer of concrete [11].

3 Continuous Fiber-Based Reinforcements

Fibers and continuous fiber-based materials (traditionally referred to as technical textiles) offer three main advantages over conventional metal based materials. These are – highly adjustable mechanical properties (tenacity, elongation, shrinkage, Young’s

modulus), high ratio of strength to weight, and variable porosity. These advantages have given rise to a wide range of textiles tailored for specific applications, from filters (for any fluid) and clothing (from t-shirts to spacesuits) to fiber composite components.

The high adaptability of textiles for specific purposes is the result of their multi-step, multi-scale production process, illustrated in Fig. 1 below. The properties of the resulting product can be adjusted and/or influenced in every process step, beginning with the choice of material occurring at the fiber stage. The next steps, yarn and fabric production, both offer various different processes and parameters to adjust the properties of the final product. In the case of composites, the matrix material and production process offer further opportunities for property adjustment.

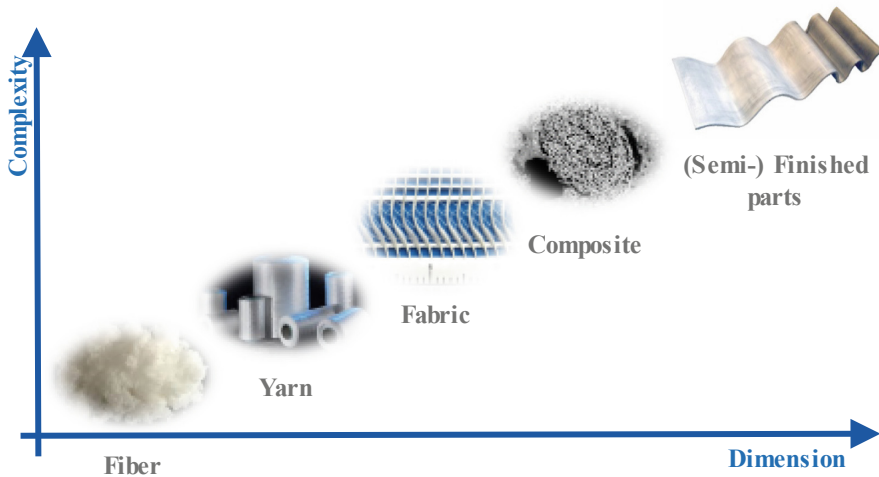


Fig. 1. Multi-scale production process of textile reinforced parts

In the following subsections, different parameters and processes relevant for continuous fiber-based reinforcement of 3D-printed concrete in the various production stages are described briefly.

3.1 Fiber Material Selection

The most important parameter determined in the selection of fibers of the textile production is the choice of material. The most commonly used fiber materials for reinforcement textiles are carbon fibers, glass fibers and high performance polymer fibers, such as aramid [12]. Other fiber materials being researched are basalt fibers [13] and natural fibers, such as hemp or flax [14]. It is also possible to combine different materials in a single fiber, for example via the production of bi-component fibers. Here, two different materials are combined to achieve enhanced properties which are not possible when using only one material [15]. An example is core-sheath fibers with a core of a high strength material wrapped with a material providing high alkaline resistance.

Another parameter in the fiber stage is the shape of the cross-section of the fiber. Usually, man-made fibers have a circular cross-section. However, the adjustment of the cross-section allows for special properties. For example, clover shaped fibers have a higher surface to mass ratio, which is beneficial in filter applications [16].

An additional parameter is the adjustment of the surface properties of the fibers, which are critical for the quality of bonding between the fiber and any matrix material as well as for haptic properties. In addition, fibers are usually coated with a sizing agent designed to protect the fiber during processing and to improve fiber-matrix bond strength.

3.2 Yarn Development and Processing

With the exception of nonwovens, fibers are spun into yarns before further processing them into fabrics. Figure 2 below illustrates selected yarn structures.

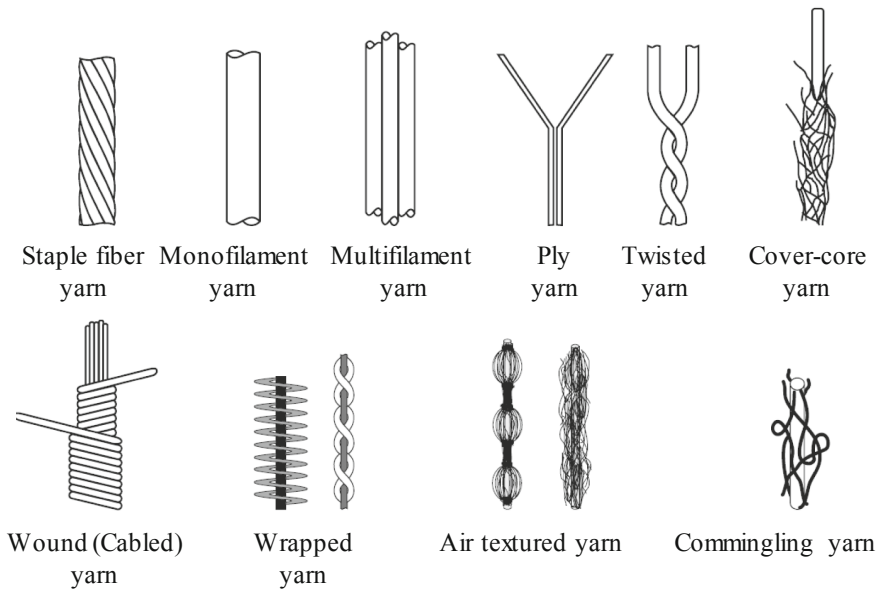


Fig. 2. Selected yarn structures [12]

Reinforcement fibers are usually produced and processed as continuous filaments. In case of natural fibers, or if highly flexible properties are needed, short fibers are processed, with fiber lengths of a few centimeters (typically 1 cm to 3 cm). Yarns, used for reinforcement textiles, are usually multifilament yarns. In the case of special requirements, processing of other yarn types can also prove to be beneficial. A multifilament yarn consists of several hundred to tens of thousands of filaments, each with a diameter in the micron range.

It is also possible to combine different materials in one yarn via the production of hybrid yarns. The production of a hybrid yarn which consists of carbon and thermo-plastic polymer fibers, allows for the production of fiber reinforced polymer parts with an even distribution of polymer in the part [17].

3.3 Fabric Development and Processing

Textile fabrics are available in a wide range of different types, produced with different methods on different machines. The type of fabric as well as the fabric construction parameters highly influence the properties of the resulting textile. Figure 3 below illustrates some of the fabric structures commonly used for reinforcement textiles.

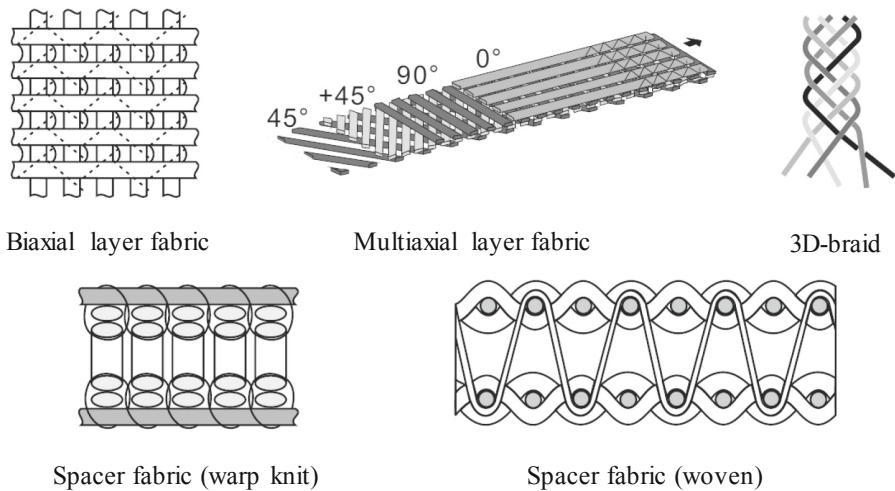


Fig. 3. Fabric structures commonly used for reinforcement textiles [12]

Each of the textile structures shown in Fig. 3 can be adapted for a specific application by varying production parameters. As an example, biaxial layer fabrics are produced using the warp knitting process. The process allows for variations of the yarn materials and spacing, knitting pattern and other parameters. Figure 4 shows three biaxial layer fabrics produced using the same materials but different knitting patterns, resulting in different textiles with different properties.

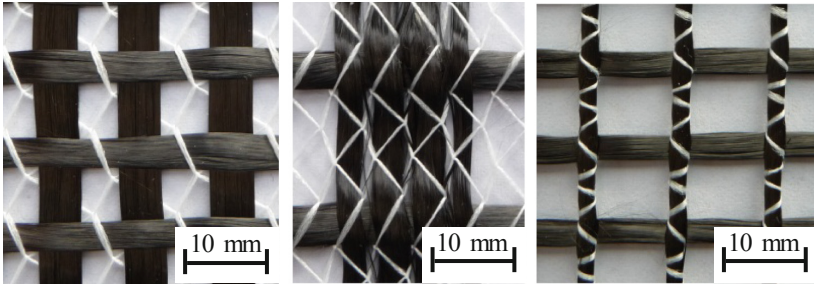


Fig. 4. Three different warp-knit biaxial layer fabrics

3.4 Composite Stage

The production of composites from textile fabrics usually involves the assembly and shaping of a textile preform and the infusion of this preform with the matrix material. Assembly usually involves the layering of multiple layers of textiles as required, sometimes with additional layers only being added where necessary. Shaping of the preform is usually done using molds. The infusion with matrix material is done using various methods (e.g. resin transfer molding or vacuum infusion). An even penetration and distribution of the matrix is critical to allow for a good force transmission into the fabrics/fibers.

4 Textile Reinforced Concrete

The above mentioned advantages of reinforcing textiles have led to research into the application of reinforcing textiles in concrete. This research began in the late 90's and has led to the advent of a new class of materials – textile reinforced concrete (TRC). While further research into the material is still necessary and ongoing, first commercial applications of the new material are available. These include precast elements such as facades, complex load bearing structures such as bridges and the application in retrofitting of concrete structures [18].

Compared to traditional steel reinforcements, reinforcing textiles offer various advantages: higher specific strength, good formability and corrosion-resistance. Since the materials usually used for TRC do not corrode, the traditionally necessary minimum concrete cover can be vastly reduced (by up to 80%). This allows for the production of thin-walled elements, which, combined with the formability of the textiles, lead to new architectural possibilities [19]. The concrete used for TRC usually uses fine aggregates with particle sizes <4 mm.

4.1 Selection of Textiles – TRC Structures

Following the stages of textile production outlined above, current textiles for TRC are made out of carbon fibers or alkaline resistant (AR) glass fibers. Both types of material are usually processed in the form of multifilament yarns. For use in the construction

industry, comparatively thick yarns with titers of up to 4800 tex (g/1000 m) are used. The most prominent type of textile in TRC are warp-knit biaxial layer fabrics. The use of warp knit spacer fabrics is being researched, but due to a complex production technology these textiles struggle with economic viability [19].

If thicker yarns are used, coating/impregnation of the textiles is necessary to ensure an even force transmission from the concrete matrix into the core of the yarn. With uncoated textiles, the force is only transmitted into the outer filaments via the outer, direct bond with the concrete matrix. The operational load is transmitted to the inner filaments via shear, which is often insufficient to fully utilize the load bearing potential of the reinforcing fibers. With coated textiles, the coating material insures improved inner bond to transmit the load to the inner filaments. This effect is visualized in Fig. 5 below.

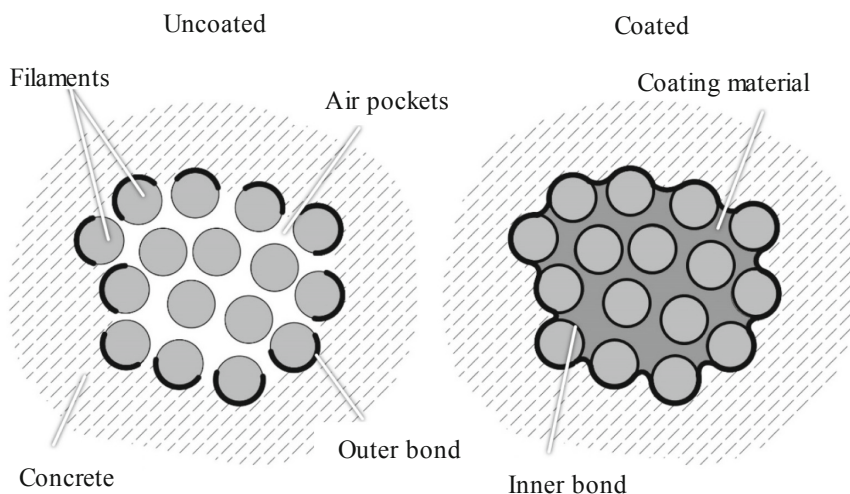


Fig. 5. Comparison of uncoated and coated reinforcing textiles

While coated reinforcing textiles offer higher mechanical performance, they are usually comparatively stiff and therefore lose some (or all) of their formability. If the required geometry of the reinforcing textile is known beforehand, it is possible to produce pre-shaped reinforcing cages, similar to reinforcing cages made of steel.

4.2 Production Methods for Textile Reinforced Concrete

Different production methods for TRC have been researched and established. Most prominent are casting, laminating and spraying. For special applications, extruding and spinning are also possible [20].

In the casting method, the textile is placed in the formwork and either clamped in place or positioned using spacers. The concrete is then cast in one work-step, filling the formwork and covering the reinforcing textile. Advantages of the casting method

include an easy automation and quick production. The disadvantage associated with this approach is the formation of relatively complex formworks, if the textiles are clamped and limitations if a large amount of reinforcement is necessary, since the concrete can only penetrate a limited amount of layers of textile.

The laminating method consists of an alternating placement of layers of textile or concrete in the formwork. The number of production steps is therefore dependent on the number of textile layers required. The laminating process allows for nearly arbitrary reinforcement ratios and precise placement of the textiles, but involves a high degree of manual labor and several production steps.

The spraying method is similar to the laminating method. Layers of textile and concrete are placed alternately, wherein the concrete layers are applied using a spraying nozzle. In addition, the spraying method can be used vertically or overhead.

5 Integration of Continuous Fiber-Based Reinforcement into Digital Concrete Production

As discussed above, textiles comprise of different materials and can consist of many different shapes which can be tailored to fit a varied set of design requirements. Therefore, the authors are confident that fitting textile reinforcement solutions for the different approaches to digital concrete production development can be found. These solutions require interdisciplinary collaboration of experts from various fields of research, such as robotics, civil engineering, architecture and textile engineering.

The authors also propose one specific example for a viable research approach for the integration of textiles into digital concrete production for which the first pretests are currently ongoing. Initially, a semi-automated process is evaluated. In the first step, the yarns and preform textile are prepared and the textile reinforcement is fixed in place utilizing a frame, with the textile placed vertically. The concrete matrix is then printed through the textile and stacked layer by layer, until the textile is covered and the production process is finished. The deposition of the concrete mix i.e. volume and mass flux, rate of deposition, etc. are controlled based on a pre-defined algorithm. Based on the quality requirements, the parameters can be actively and remotely modified in order to account for the geometric shape variability. The proposed approach is illustrated in Fig. 6.

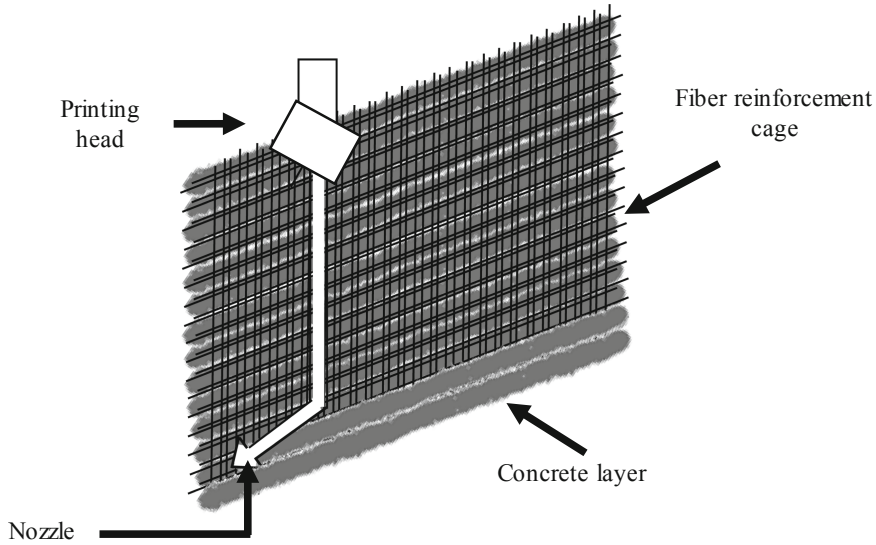


Fig. 6. Possible approach for the integration of textile reinforcement into the 3D-printing process

6 Conclusions

One of the critical issues of the relatively new research are of digital concrete production is the integration of reinforcing materials into the production process. Some approaches already exist, most utilizing traditional steel reinforcement or short fibers. Continuous fiber-based reinforcements (textiles) offer a promising alternative reinforcing material- textiles are a versatile class of materials that can be adapted for nearly every purpose, and reinforcing textiles are already used in textile reinforced concrete. In an interdisciplinary collaboration of mechanical engineers, civil engineers, architects, designers and textile engineers, solutions for the integration of textile reinforcements into digital concrete production are proposed and a cursory evaluation is conducted. Future work involves the development of a fully automated unit cell for production of complex TRC panels.

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3D Concrete Printing on Site: A Novel Way of Building Houses?

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Abstract. As a result of the constantly increasing world population and its purchasing power, it becomes more and more clear that raw materials are finite and the capacity of the earth to renew the stock of raw materials is almost exceeded. This is also important for construction industry as half of the extracted materials and about one third of the water consumption is absorbed by this sector. During the last years, a lot of progress has been made in creating more energy efficient buildings, but unfortunately, construction represents at this moment still 40% of the energy demand in Europe and 36% of the total CO₂ emission [1]. However, the construction sector offers significant potential to handle these struggles and a possible solution to improve the sustainability is through automated construction by for example 3D printing the structural components. This new way of manufacturing has the advantage that there is no need for energy demanding and expensive molding, there is a larger freedom of form and there is the opportunity to use the material in a more eco-friendly way since it is only used where necessary. However, before acceptance of this technique on the construction site, it is necessary to compare the structural behavior of printed and cast specimens. For that reason, two wall types were tested on their compressive strength and also two types of reinforcement above a window opening were investigated through 3-point bending tests. These results showed that, in general, the mechanical performance of the suggested wall types is greater than that of traditional walls consisting of brickwork. This, in combination with the lack of molding and the higher construction speed, can accelerate the application of 3D printing on site.

Keywords: 3D printing on site · Construction · Mechanical performance

1 Introduction

The development of digital construction processes for the production of concrete components and structures directly on the construction site is a decisive step towards the introduction of the “industry 4.0” concept into the construction industry. The technological and economic potentials (accelerated construction time, lack of formwork, reduced construction cost, etc.) of digital concrete construction have now been recognized by many industrial stakeholders and the extend of innovation in this field is increasing month by month.

Most current applications of 3DCP are driven by original architectural and design concepts, which require novel production techniques. However, considering today’s mainstream demands with respect to architecture and structural design, high geometrical complexity is not the main priority of the construction industry and more attention should be paid to real-scale, mainstream applications.

Before full acceptance of this technique on the construction site, it is necessary to compare the behavior of printed and traditional fabricated structural elements. For that reason, two different wall types (i.e. structural wall and isolated wall) were tested on their compressive strength and also two different types of reinforcement (i.e. reinforcement bars and a reinforcement mesh) above a window opening were compared through 3-point bending tests. These results showed that, in general, the mechanical performance of the suggested wall types is higher compared with a traditional wall consisting of brickwork. This in combination with the lack of molding and the higher construction speed, can accelerate the application of 3D printing on site.

2 Materials and Methods

2.1 Mix Composition and Print Process

The material used for this research (Weber 145-1) has been developed by Saint-Gobain Weber Beamix. To fulfill all the requirements [2] with regard to printing, the material consists out of Portland Cement (CEM I 52.5 R), a siliceous aggregate, limestone fillers, rheology modifying agents and a small amount of polypropylene fibers to reduce the crack formation [3]. The water-to-dry mortar ratio used in this research equals 0.15. The structural components were printed by using a 4-degree of freedom gantry robot (BOD2), developed and designed by the company 3D Printhuset (Copenhagen). During this research, a rectangular nozzle ($40 \times 15 \text{ mm}^2$), equipped with side towels and grooves, was used. The layer height and applied printing speed equal 15 mm and 150 mm/s.

Within the scope of this research, two essential structural components (i.e. wall and window lintel) were tested in order to make the comparison with traditional constructions. The first test series consists out of two different wall types. More specifically, a structural and an insulated wall type were tested and the geometry of both elements is represented in Fig. 1(a, b). The height of the specimens equals in both cases 66 cm. In the second test series, two alternatives to reinforce the window lintel were tested. More specifically, reinforcement bars ($\varnothing 10 \text{ mm}$) were integrated above the

window opening in the first test setup, while the second alternative was the integration of a small reinforcing mesh (MURFOR Compact E, Bekaert). Both types of reinforcement were integrated manually during printing and the geometry of these elements is given in Fig. 2.

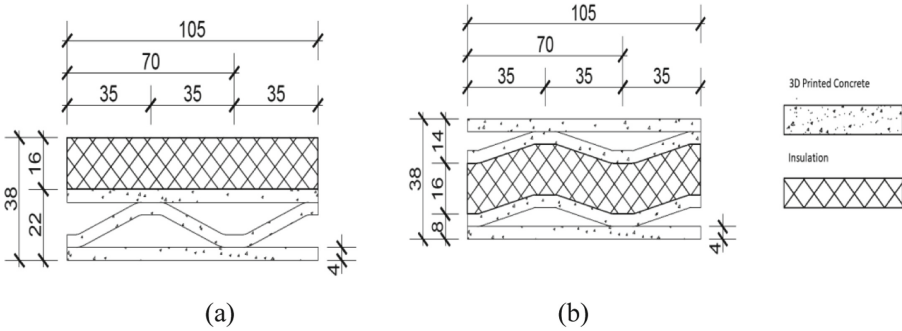


Fig. 1. Top view of the different wall types: (a) structural wall and (b) insulated wall (dimensions in [cm])

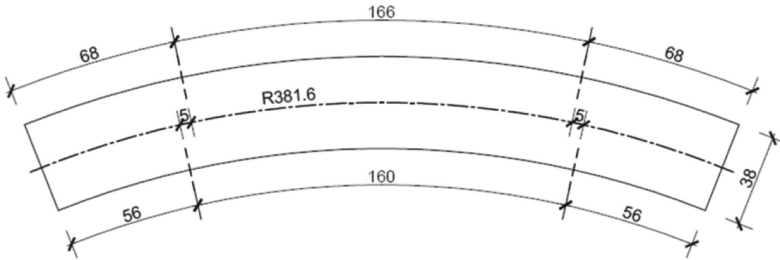


Fig. 2. Top view of the printed specimens, fabricated to investigate two reinforcement alternatives above a window opening (dimensions in [cm])

2.2 Compressive Strength

The mechanical performance of both, the structural and insulated wall, was tested by means of a compression test. The compressive strength f_c [kN/m²] (Eq. (1)) was measured for two specimens loaded perpendicular to their print direction during a load controlled test at a rate of 1 kN/s. To obtain representative results, the evenness of the top and bottom surface plays an important role and, therefore, both surfaces were smoothed before testing and a hardboard was used during the compression test to ensure a uniform distribution of the load.

$$f_c[\text{KN/m}^2] = \frac{F}{A} \quad (1)$$

Within this formula F [kN] is the failure load and A [m²] is the actual area of the printed specimen on which the load is acting.

2.3 3-Point Bending Test

The failure load F_t [kN] of the printed elements with reinforcement was measured by performing a 3-point bending test (Fig. 2). During this test, the load was applied by using a hydraulic jack (10 ton Amsler jack), placed centrally on an I-profile. The loading speed for both test specimens was equal to 1 kN/s. In addition to the breaking load, the vertical displacement at 6 different positions was measured by using Linear Variable Differential Transformers (LVDT's) (Fig. 3).

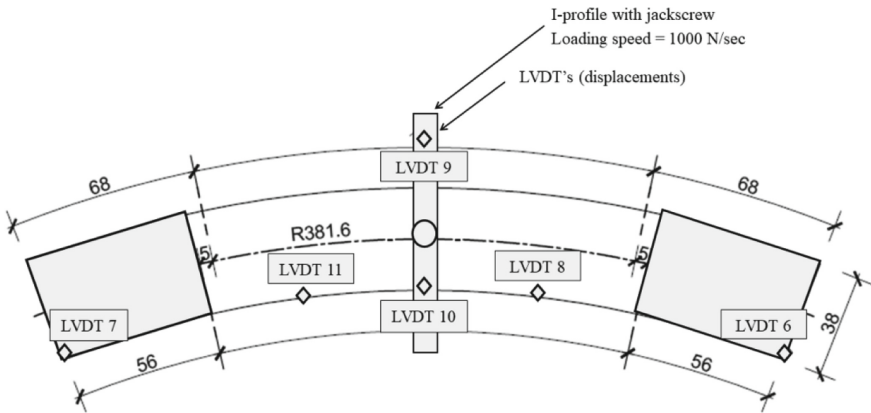


Fig. 3. Top view of the of the test setup, including the LVDT positions (dimensions in [cm])

3 Results and Discussion

3.1 Compressive Strength

Table 1 represents the failure load of the different wall types measured during the compression test. Based on this, one can conclude that the compressive strength of both wall types is by approximation the same. In case of a traditional wall, built up from building bricks (288 × 188 × 138 mm), the compressive strength equals approximately 20 MPa [4]. Comparing the latter with the results mentioned in Table 1, one can conclude that the mechanical performance of the printed specimens is much better compared to the traditional construction way. As the height/width ratio is kept similar for both wall types, the failure mechanism during the compression test is the same (Fig. 4).

Table 1. Failure load of the different wall types measured during compression test

		Structural wall		Insulated wall	
F	[N]	2012370	2126700	2711500	3324250
A	[mm ²]	66000	53000	86000	98000
f _c	[N/mm ²]	30.49	40.13	31.53	33.73
f _{c,mean}	[N/mm ²]	35.31		32.63	

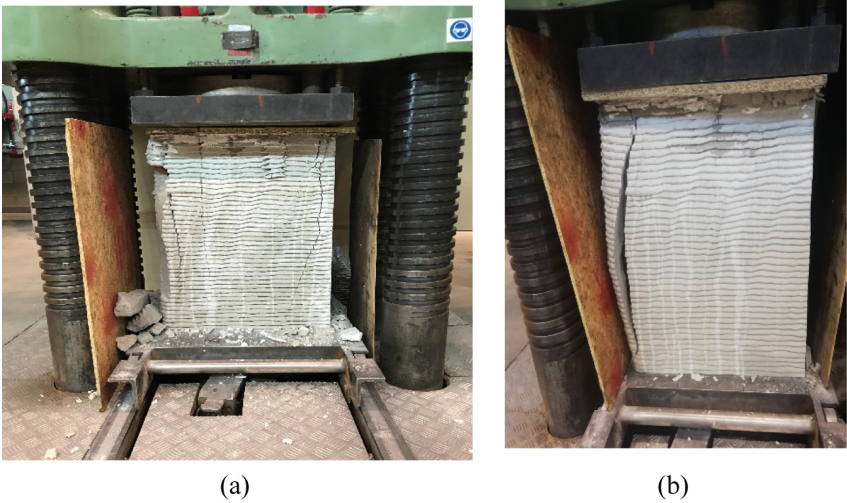


Fig. 4. Failure mechanism in case of (a) structural wall and (b) insulated wall type

3.2 3-Point Bending Test

Table 2 represents the failure load of the different wall types and the corresponding displacement measured during the 3-point bending test. One can conclude that the addition of a reinforcement bar resulted in a higher failure load compared with the introduction of a reinforcement mesh, which is also represented in the load-displacement curves of both reinforcement alternatives (Fig. 5). Comparing these results with a traditional lintel, placed above a window opening, which has a failure load of approximately 25 kN [5], the results are higher for both. Figure 6 gives an overview of the specimens after failure.

Table 2. Failure load measured in case of two alternatives for window lintels (i.e. reinforcement bars and mesh)

		Reinforcement bars	Reinforcement mesh
F_t	[kN]	65.62	33.74
LVDT 6	[mm]	16.96	9.25
LVDT 7	[mm]	12.30	7.62
LVDT 8	[mm]	-6.69	-11.24
LVDT 9	[mm]	-13.12	-16.07
LVDT 10	[mm]	-11.63	-17.83
LVDT 11	[mm]	-6.49	-12.29

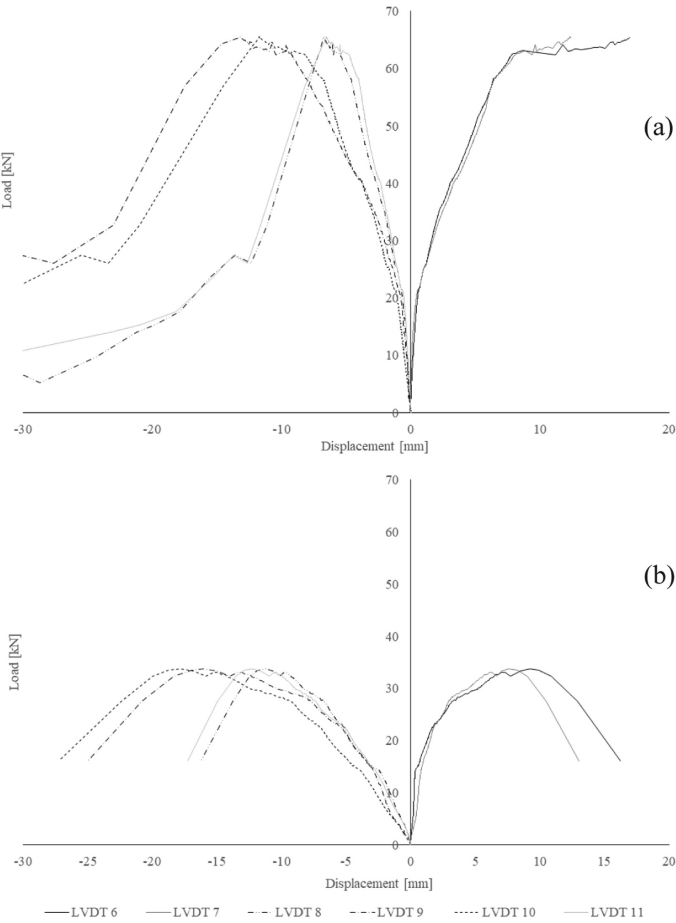


Fig. 5. Load-displacement curves for two reinforcement alternatives: (a) rebars and (b) reinforcement mesh

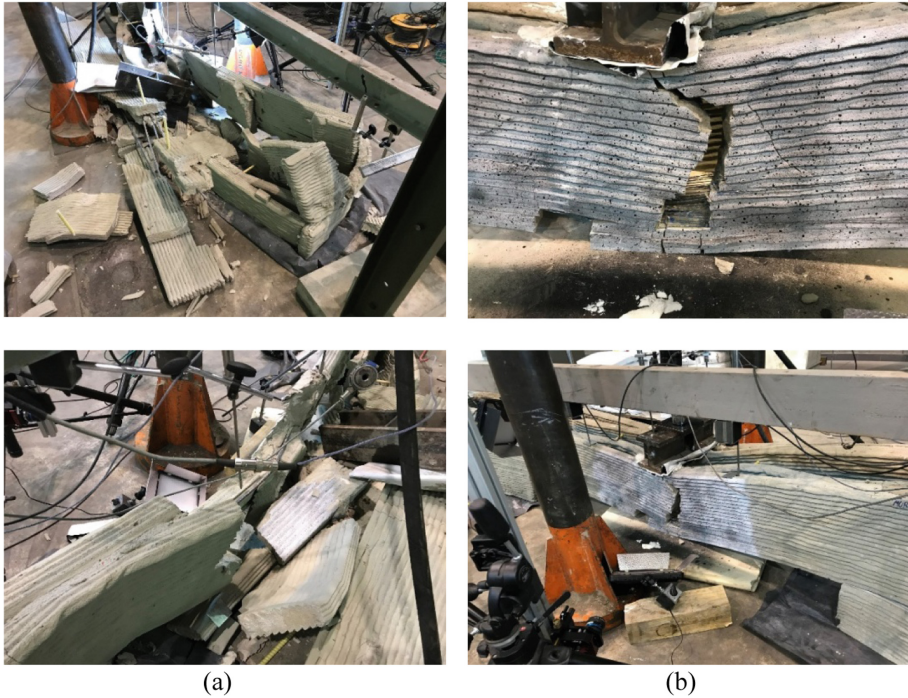


Fig. 6. Failure mechanism for two alternatives: (a) the introduction of rebars and (b) reinforcement mesh

4 Conclusions

Within the scope of this research, printed alternatives for two constructive aspects (i.e. traditional masonry and the introduction of a lintel above window openings) of a traditional house are investigated. The following conclusions could be drawn:

- The mechanical performance of the structural and insulated wall type, measured by means of a compression test, do not differ in a significant way;
- The compressive strength is for both wall types higher than the compressive strength of a wall erected by means of traditional masonry;
- The load at failure of the lintel alternatives is in both cases higher than the traditional one;
- The addition of reinforcement bars results in the best option in case of printing window openings.

Acknowledgements. The authors would like to acknowledge the support by EFRO for the C3PO-project (B/15100/01). The support of WEBER for the delivery of the cementitious material is gratefully acknowledged.

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Design Optimization for 3D Concrete Printing: Improving Structural and Thermal Performances

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Abstract. This paper focuses on optimizing the shape of prefabricated building components that are produced using 3D concrete printing (3DCP) techniques. The proposed method is to improve the structural and thermal properties using heuristic optimization algorithms, as such that they meet the minimum standards determined by building design codes. First, a case study is constructed that is based upon an existing module design found in literature, and a single segment from this design is isolated. The influence of the overall shape and the curvature of the infill line is investigated, and the structural performance is optimized for the hardened material state. In a second attempt, the heat transfer through the segment is also minimized. In parallel to the design's optimization process, of course, the manufacturing challenges and process limitation need to be considered as well. Therefore, the influence of the infill line on the buildability of a 3DCP element is also demonstrated in a fresh material state (i.e. during printing). For this, the complete printing process of a wall segment is simulated and allows for the prediction of printing failure, elastic buckling and plastic collapse. Based on the outcome of the FEM-based calculations, a design could then be marked fit for printing or allow for further optimization.

Keywords: Concrete printing · Design optimization · Structural and thermal analysis · Process simulation

1 Introduction

In this paper, a combined approach of structural and thermal design optimization is considered for the production of 3D concrete printed building components. The goal is to print fully-functional components that meet all technical requirements without too much post-processing (e.g. adding additional structural reinforcements or external thermal insulation which requires additional material and human resources). In order to achieve this goal, simulation models are used to predict the behaviour of different design proposals. When a parametric model becomes available, optimization techniques could then be applied to determine the most optimal design parameters or

provide information with regard to better design decisions. To demonstrate the proposed method, a case study is developed, based upon the work of [1]. In this paper, the first 3D-printed office building was presented, within the context of ‘The Office of the Future’ which was built in the city of Dubai (United Arab Emirates). The completed project consisted of four modules, each made from multiple segments that were joint together. Each segment is U-shaped with a maximum length, height, and width of 8.1 m, 2.1 m and 2.1 m respectively (Fig. 1). However, in the paper no mentioning was made to the origin of the shape, or the reason for the exact curvature and frequency of the sinusoidal infill line. Was it purely aesthetical and could the design have been further improved by optimization techniques?

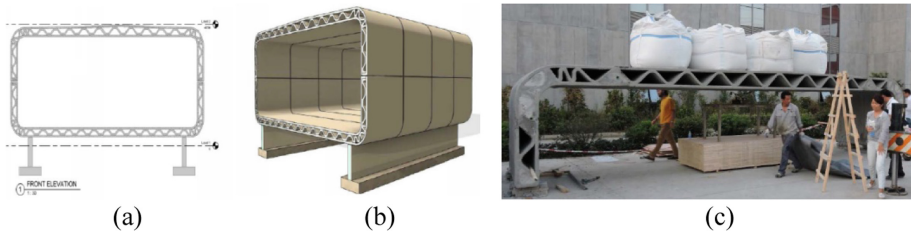


Fig. 1. The first 3D-printed office building (a) cross section, (b) architectural perspective, and (c) experimental setup. Illustrations from [1].

2 Case Study

For this conceptual design study, a similar - but simplified - module as in [1] was constructed, consisting of four segments with average length, height, and width of 4.8 m, 1.5 m and 1.9 m respectively (Fig. 2). The dimensions of the segments are within the maximum reach of the current robotic setup at our lab facility (Magnet-Vandepitte Laboratory). As such, when a successful design would be found, it could also be printed. For this paper only the top segments (green and red segments) are studied.

For the design’s optimization, we chose to apply heuristic optimization methods, in contrast to previous work [2, 3] that used gradient-based optimization techniques (i.e. topology optimisation). The reason for this is that when designing for 3D concrete printing, the maximum complexity of a design is still limited with the current state-of-the-art of concrete printing. Despite many advances made to improve the maximum overhang angle of the freshly-printed material, topology optimization results remain very hard to transform into printable designs.

A second reason for using heuristic optimization models is that they are ideal for optimizing predetermined shapes. Like in this case study, the overall build-up of the roof structure is already arranged, consisting of three curve-like print paths: an outer layer, an inner layer, and a sinusoidal internal infill line (Fig. 3). Therefore, the overall design freedom is already largely restricted making evolutionary solvers like genetic algorithms (GA) or simulated annealing (SA) more suited. Additionally, they allow for a high degree of interaction with the user, are quite forgiving and flexible (e.g. able to solve a wide variety of problems). One weak aspect is that these optimization methods

are slower than gradient-based algorithms. In this regard, the computation time required to solve a single simulation needs to be as fast as possible. Therefore, some simplifications in the modelling are made. First, symmetry is considered, so only half of the design domain of one segment is studied. Secondly, the load conditions are simplified to one symmetric load case, forming the worst-case combination with the vertical (service and snow) and horizontal (wind) loads. In the current demonstration, the self-weight of the concrete is neglected.

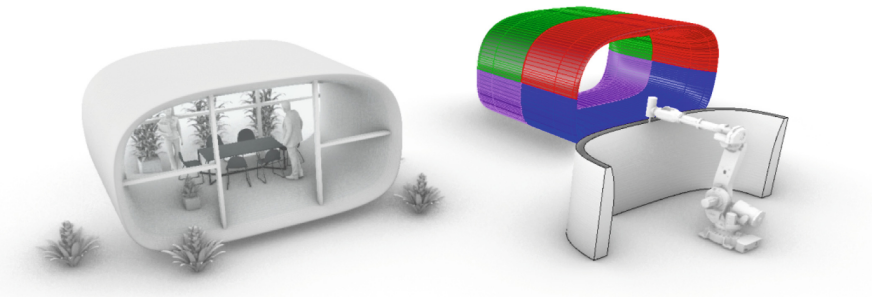


Fig. 2. Bird's-eye view on the case study discussed in this work, including the robotic setup.

2.1 Constructing the Parametric Model

The first step contains the construction of the parametric model. For this, Rhinoceros and Grasshopper are used. The basic shape (centre line) of the segment (presented as a thick blue line in Fig. 3a) was drawn in Rhinoceros and forms the basis of the segment's structure. This geometric component cannot be adjusted by the optimization algorithm. From this curve the outer and inner curves (red lines) are created based on a number of input parameters. Among others, the thickness of the structure and the curvature are controlled in several points. From these points, also the sinusoidal curve is created. The latter joins the two separate paths together and a mesh can be generated (Fig. 3b). The curvature of the sinusoidal curve is controlled using a custom component called 'Bezier Span Extensible' in which Bezier curves are made using a set of points and vectors. In the end, the total number of independent variables was 18. The

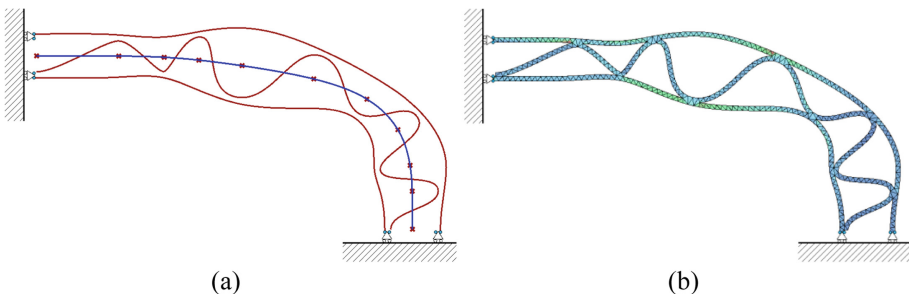


Fig. 3. Overall structural build-up of the case study: (a) 2D model showing fixed centre line (blue) and the parametrically-defined print curves (red), and (b) simplified FE mesh containing 600 elements.

print path thickness remains constant and equals 30 mm, a practical single layer width for concrete printing.

The construction of the parametric model is one of the most important steps of the design process, as it largely influences the degree of optimization that is achievable. The design's freedom and associated quality of the solution is restricted to the provided parameters and their respective domains. To cope with this problem, another advantage of using evolutionary solvers is presenting itself. Because the run-time process is highly transparent and browsable, early optimization trials present useful opportunities for changing design decisions and help steer into exploring sub-optimal branches and superficially dead ends.

2.2 FE Simulation

Concerning the simulation of the structural and thermal performances, a custom grasshopper script was written to handle the FE analysis. Rolling supports are provided at the bottom of the structure, while symmetry constraints are imposed to the upper-left part. The combined action from service and snow loads is applied to the top vertices, considering the local slope of the outer curve, and the horizontal wind load was applied from left to right. The averaged magnitude of the vertical and horizontal forces is around 1:1. Both analyses are performed with a linear FE solver considering the following material properties of the concrete: Young's modulus (E) 30 GPa; density (ρ) 2500 kg/m³; Poisson's ratio (ν) 0.2, thermal conductivity (k) 1.0 W/(mK). For the thermal analysis, the equivalent thermal conductivity and mean U-value are calculated using a temperature gradient of 20 K between the inner and the outer curve, and adiabatic internal voids. Both analyses combined have an average calculation time of less than 2 s with a mesh containing roughly 7000 elements.

2.3 Structural Optimization Study

In the first optimization study, the structural performance of the structure is optimized in relation to its total weight (g). The goal is to minimize the average deflection (δ) of the top part, while using as little material as possible. Both the Galapagos and Octopus solvers (plug-ins inside Grasshopper) can be used. However, because the latter introduces the Pareto-Principle for multiple goals, it is a more interesting and thus preferred solver (i.e. it allows to explore the full set of optimized solutions). In Fig. 4, we present some of the optimized solutions after 11 h of calculation time containing 16.000 evaluations. The set of results that is presented, follows the pareto front. For an increasing deflection, the self-weight is decreasing. A visual depiction of the pareto front can be observed in Fig. 6a, where also the exact positions of solutions in Figs. 4a–f are highlighted. Important to note is that not all combinations of variables give a valid structure. While the FE analyses are still carried out, they can be recognized by having extreme performances; very low self-weight or very low deflection. Furthermore, almost all optimized solutions in the pareto front show to have a wider base and top, in contrast to the middle of the structure that is narrowing. It is also noted that in the subsequent solutions when the deflection rises, only minimal improvements in the self-weight are found.

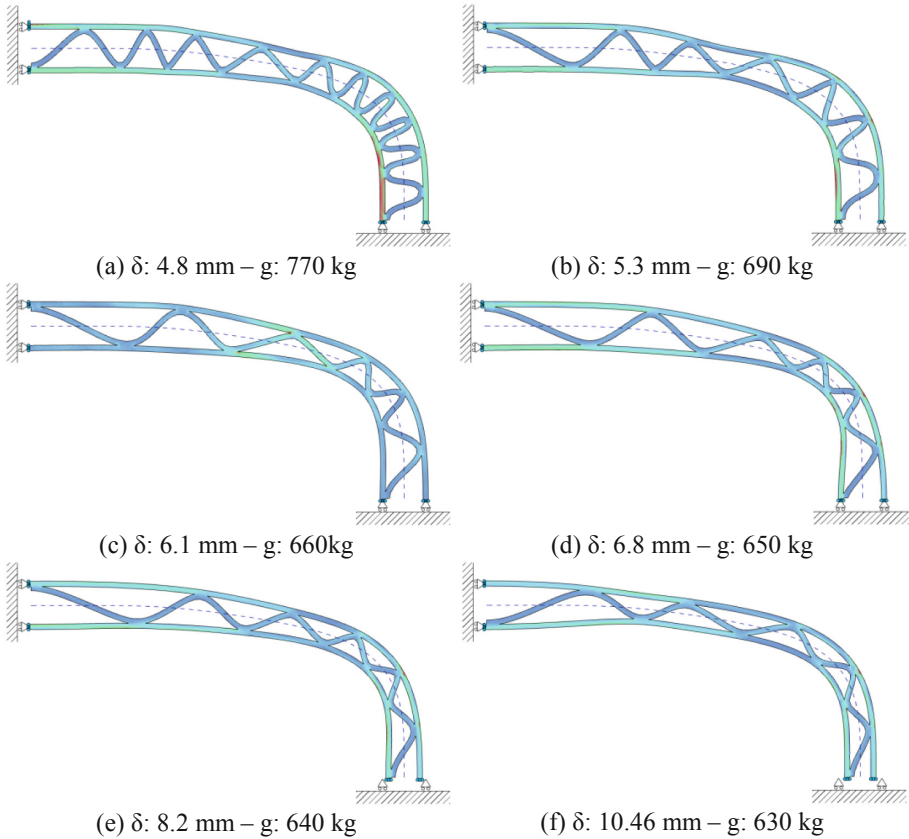


Fig. 4. Set of optimized results captured from the Rhino viewport (colours: von Mises stress).

2.4 Structural and Thermal Optimization Study

In the second study, not only the structural performances and the self-weight are optimized, but also the thermal performances are investigated. Again, the Octopus solver is used and allows for three-dimensional optimization. Consequently, a third axis in the optimization panel is added, on which the thermal transmittance through the modules is shown. This transmittance, i.e. the mean U-value, is measured in $\text{W}/(\text{m}^2\text{K})$. According to recent building codes, the Belgium limit value is $0.24 \text{ W}/(\text{m}^2\text{K})$. Like the 2D pareto front line, now, the Delaunay front mesh is sought after (Fig. 6b) and Fig. 5 presents the optimized solutions. These focus on results that have a good thermal performance. The calculation time is roughly 12 h. The main observed phenomenon is that the curvature of the infill line is different from the previous results. Now, sharp corners are present. Finally, the optimized design in Fig. 5d is chosen, and a final arrangement for the 3D-printed module is shown in Fig. 7.

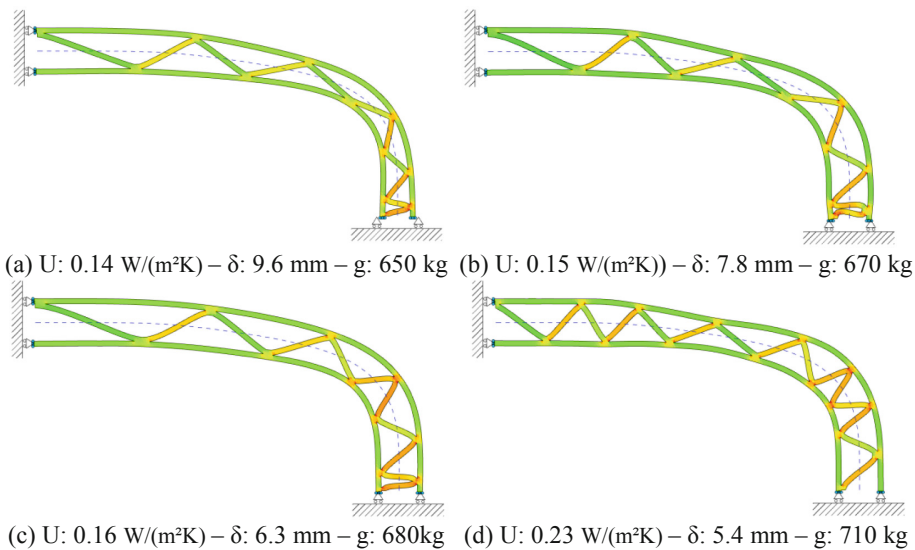


Fig. 5. Set of optimized results captured from the Rhino viewport (colours: heat flux).

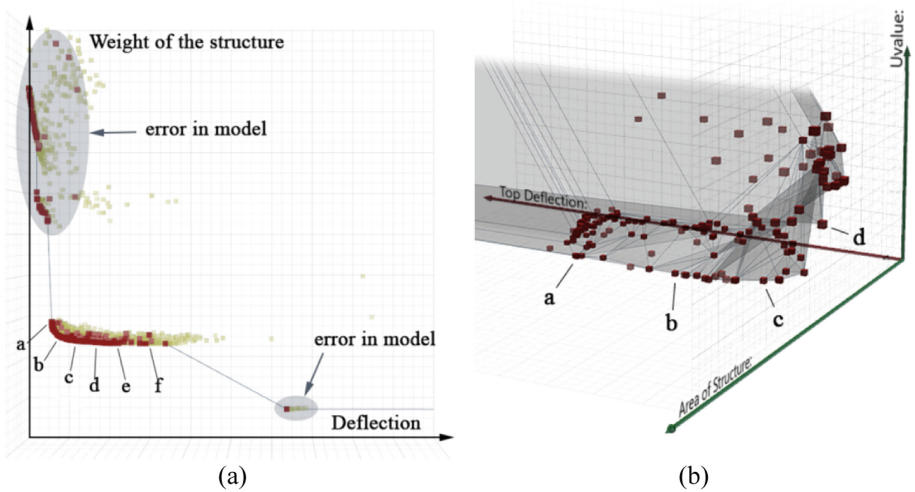


Fig. 6. Pareto front of the solutions from the multi-objective optimization study in Octopus. (a) Structural optimization and (b) Multi-physics study.

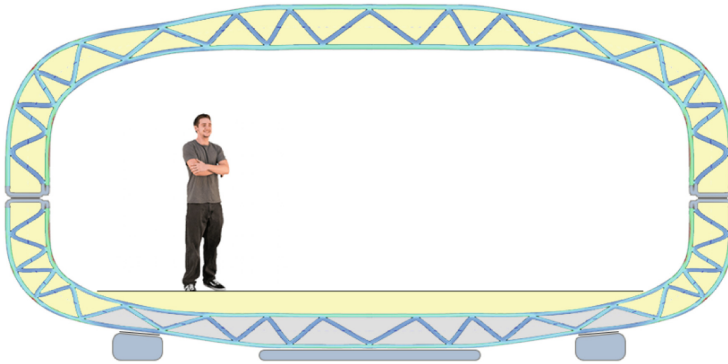


Fig. 7. Final arrangement for the to-be 3D-printed case study, optimized for its structural and thermal performances.

3 Process Simulation

In the previous section, a design was optimized according to its structural and thermal performances in the hardened material state and for its final assembled orientation. Of course, the optimized design still needs to be produced, preferably printed in one piece and in a continuous layer-wise fashion. To predict the probability of print failure and estimate the maximum print speed, a print simulator was developed, discussed in [4]. Future work should focus on using such process simulations to predict the buildability of the developed component. Additionally, a combination of process simulation and evolutionary solvers could also investigate the differences in performances between several sub-optimal branches and help make design decision. In Fig. 8, a similar sinusoidal segment was imported in the process simulator and the influence of the infill pattern was analysed. It was found that the contact of the sinusoidal shape largely improved the buildability of the structure (i.e. lowering the buckling length and as such to postpone elastic buckling). Therefore, a higher print speed could be obtained as for a design without infill pattern.

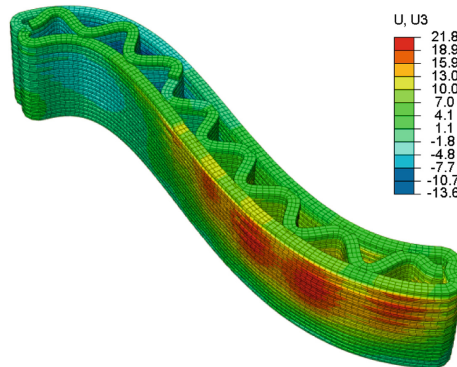


Fig. 8. Results from the numerical process simulation performed in Abaqus [4].

4 Conclusions

In this paper, a heuristic method was proposed to optimize the structural and thermal properties of 3D-printed building components. Using these so-called evolutionary solvers, a broad range of different design decisions could be analysed and optimized to meet the standards determined by recent building design codes. The study of the curvature and frequency of the infill line showed to give a slight preference to using sharp corners, probably in an aim to reduce the heat flow through the module. These structural and thermal performances were optimized for a hardened material state. In a second study, the manufacturing challenges and process limitation were considered, and a demonstration of a concrete printing simulation was presented. Future research should link both applications in order to provide a complete design methodology when it comes to the engineering of digitally-fabricated building structures.

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Flexural Behaviour of AR-Glass Textile Reinforced 3D Printed Concrete Beams

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Abstract. 3D concrete printing (3DCP) enables automation of construction manufacturing through digital design and workflow, adding value through high degrees of form freedom. The process constraints during the printing, however, hamper the application of reinforcement and hence limit the ductile behaviour that is achievable in 3D printed concrete structures. Although a number of reinforcement strategies have been developed and these strategies can to some extent address these limitations, the reinforcement challenges of 3D printed concrete structures are not satisfactorily addressed yet. This paper proposes another reinforcement strategy of incorporating alkali-resistant (AR)-glass textile between the printed concrete layers. To validate the strategy, small-scale printed concrete beam specimens reinforced with one to three layers of textiles were tested under three-point bending. The results were compared to those obtained from equivalent ‘cast’ specimens. Comparable flexural behaviours were observed between the cast and printed textile reinforced concrete (TRC) specimens. Moreover, the flexural behaviours of printed specimens exhibited lower scatter than the flexural behaviours of cast specimens, which was probably due to the precise digitally controlled printing process. Future research should focus on the application of textile reinforcement in more complex 3D printed concrete structures.

Keywords: 3D concrete printing · Reinforcement · AR-glass textile · Flexural behaviour

1 Introduction

3D concrete printing (3DCP) is an extrusion-based additive manufacturing technique in which the concrete layers are deposited on top of each other to gradually form objects without the need of formwork. As a disruptive technique, 3DCP is attracting significant attention worldwide [1, 2]. Despite the many advantages of 3DCP, its application is

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F. P. Bos et al. (Eds.): DC 2020, RILEM Bookseries 28, pp. 728–737, 2020.

https://doi.org/10.1007/978-3-030-49916-7_73

still limited by the difficulty of incorporating reinforcement to obtain the desired strength and post-cracking ductility [3]. In order to address this limitation, a number of reinforcement strategies have been proposed, including: printable fibre reinforced concrete; external reinforcement arrangements; 3D printed formworks; incorporation of high strength steel wires into the concrete beads during printing; concrete printing around fixed steel reinforcement; and parallel multi-arm printing of concrete and reinforcement [3, 4]. Although these strategies can to some extent address the limitations of 3D printed concrete structures, sufficient reinforcement of 3D printed complex geometry (e.g. doubly curved) concrete structures remains a challenge [5].

In recent years, the application of textile reinforced concrete (TRC) in construction industry has received much attention [6, 7]. Textile reinforcements are usually made of materials such as carbon, basalt, and glass fibres that can meet the growing durability and lightweight requirements for the concrete structures [7]. Moreover, TRC is of high formability compared to steel reinforced concrete [6, 7]. Therefore, TRC is particularly competitive for complex thin-shell structural elements with a fine grain concrete matrix [6, 7].

Given the potential of TRC, alkali-resistant (AR) glass textile reinforcement was chosen in this study to investigate the structural potential of textile reinforced 3D printed concrete. Twenty-one TRC specimens were manufactured to examine the influences of manufacturing method (cast and printed) and textile layers (one to three layers) on the flexural performance of TRC specimens.

2 Experimental Program

2.1 Specimen Design

In total 21 specimens, including 12 cast and 9 printed, were prepared and tested under three-point loading (Table 1). The specimens were 450 mm in length, 100 mm in width and 20 mm in depth. The span length was 400 mm. A varying layer of textiles (one to three layers) were placed into the concrete beams with 5 mm spacing between neighbouring layers, positioned as shown in Fig. 1. The concrete cover thicknesses were 5 mm for all specimens. Four nominally identical specimens were manufactured for the cast specimens, while three nominally identical specimens were manufactured for the printed specimens. The labelling of each specimen is named as follows: (1) “C” and “P” indicate the cast and printed specimens, respectively; (2) “L” and the number afterwards indicate the textile layers; and (3) the last number “1”, “2”, “3”, and “4” to differentiate between the nominally identical specimens.

Table 1. Details of test specimens.

Specimen	Length (mm)	Span (mm)	Width (mm)	Depth (mm)	Number of textiles
C-L1-1, 2, 3, 4	450	450.0	100.0	20.0	1
C-L2-1, 2, 3, 4	450	450.0	100.0	20.0	2
C-L3-1, 2, 3, 4	450	450.0	100.0	20.0	3
P-L1-1, 2, 3	450	450.0	100.0	20.0	1
P-L2-1, 2, 3	450	450.0	100.0	20.0	2
P-L3-1, 2, 3	450	450.0	100.0	20.0	3

Note: The actual specimen sizes varied due to the placement of textiles and manufacturing errors.

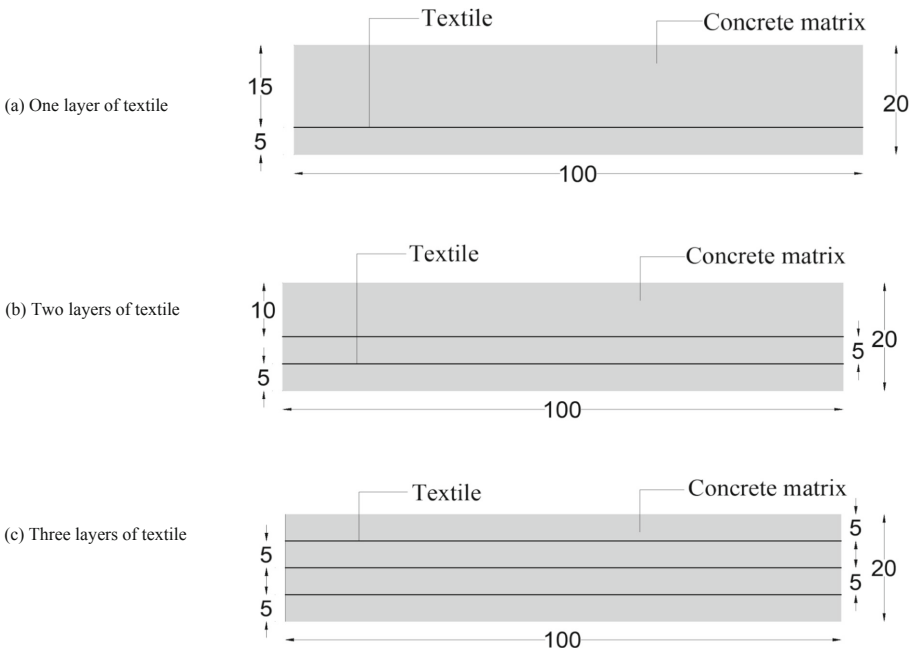


Fig. 1. Specimen details (Units in mm)

2.2 Materials

The mix proportions of concrete are provided in Table 2 with a target compressive strength of 100 MPa after 28 days. During the mixing process, the dry components were mixed with water and a polycarboxylate based superplasticizer to lower the water/binder ratio and hence increase the workability and strength. A retarder, formed by amino tris (methylene phosphonic acid), citric acid and formaldehyde, maintained enough open time, facilitating a constant flow during printing [8]. The concrete also contained 12/0.18 mm length/diameter polypropylene microfibers to reduce the possibility of plastic shrinkage. The compressive strength of the cast concrete was determined by following the BS EN 12390-3:2009 [9]. Based on the test results, the

Table 2. Mix proportions of concrete

Constituents	Quantity (kg/m ³)
Sand	1244
Cement 52.5	581
PFA	166
Silica fume	83
Water	212
Retarder Delvo	4.2
Spa Glenium 51	8.3
PP Fibers	1.2

concrete compressive strength measured with 100 mm cubes was 102 MPa at 28 days with a coefficient of variation of 0.057.

Alkali-resistant (AR)-glass fibre textile was used as the reinforcement, which was provided by the Institute for Textile Technology (ITA) of Aachen University (RWTH), Germany. The textile had the warp yarns with 8 mm spacing and weft yarns with 8 mm spacing. The reinforcing area per 100 mm width was 16.12 mm². The tensile elastic modulus and the tensile strength of the textile (in both directions) were 70 GPa and 1800 MPa, respectively [7].

2.3 Experimental Preparations and Instrumentations

For both cast and printed specimens, concrete panels were prepared and later the required specimens were cut from these panels.

For the cast specimens, the concrete was cast into a specially designed wooden formwork. Before the casting, the formwork was greased inside to ensure a smooth bottom surface and easy demoulding. First, a thin layer (5 mm) of concrete was placed into the formwork and a trowel was used to smooth the concrete surface. Afterwards, the first layer of epoxy-coated textile was placed manually onto the concrete and a lamination roller was used to ensure the textile was evenly distributed and integrated well within the concrete. It is noted that a preliminary study conducted by the authors suggested that the epoxy-coated textile exhibits higher reinforcement efficiency than the non-coated textile. The above process was repeated until the final layer of concrete was placed and evenly finished.

After casting, the concrete panel surface was covered with plastic sheet to prevent moisture loss and impairment of the hydration of the cement, which was essential to alleviate the adverse influence of plastic and drying shrinkage cracks. The cast concrete panels were left to cure for the first 24 h and then demoulded and cured in a 20 °C water tank until the testing date. Finally, the concrete panels were cut into 100 mm wide specimens with a diamond saw.

A 15 mm diameter nozzle was used for the printing and the depth of each concrete layer was 5 mm. After the bottom layer of concrete was printed, the first layer of textile was placed manually onto the printed concrete and then the second layer printed. This process was repeated until the last layer of concrete was printed. During the printing, all

the extrusion beads were printed in one orientation, consistent with the warp direction of the textile. For both cast and printed specimens, each textile reinforcement layer contained ten yarns in the warp direction, which resulted in the reinforcement ratios (by volume) of 0.81%, 1.61% and 2.42%, respectively, for one layer, two layers and three layers textile reinforced concrete (TRC) specimens (in the warp direction). The specimens were subjected to three-point loading in a 100 kN Instron screw-driven machine. The tests were under central deflection control for the first 4 mm of deflection at a rate of 0.5 mm/min and then by the crosshead displacement set at 1 mm/min.

3 Experimental Results

3.1 Specimen Depth

The specimens' depth was measured before the tests in three locations (Table 3 and Fig. 2). The specimen depth continuously increases by placing more layers of textiles into the printed TRC specimens. Nevertheless, the depth changes for cast TRC specimens do not follow the same trend. Surprisingly, the cast TRC specimens with two layers of textiles achieve the largest depth, followed by the cast TRC specimens with three layers and one layer of textiles. However, the designed depth (20 mm) is very small and the manufacturing error can be large for the cast TRC specimens.

Table 3. Average depths of the specimens (unit in mm)

Method	One layer	Two layers	Three layers
Cast	21.3	23.3	21.6
Printed	20.9	21.7	21.8

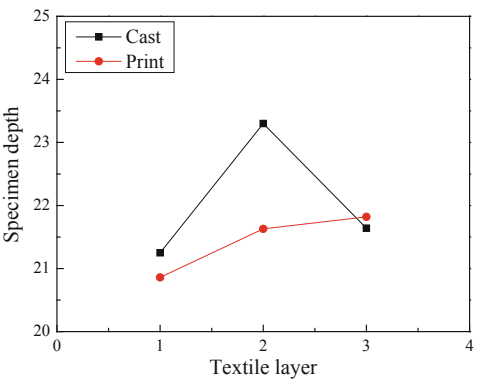


Fig. 2. Influence of textile layers on the specimen depth.

3.2 Failure Modes

Figure 3 shows the representative failure modes of the TRC specimens. Regardless of concrete types (cast and printed), most specimens exhibit a similar failure mode, that is, flexural failure after the ultimate tensile strain of the bottom layer of textile is reached (Fig. 3a). One printed specimen (P-L3-2) and one cast specimen (C-L2-1) exhibit combined flexural and shear–delamination failure, as illustrated in Fig. 3b. This combined failure mode is due to the debonding between the bottom textile and the concrete. Figure 4 shows the representative localized failure patterns. During the tests, cracks first occurred at the tension side and then began to propagate towards the compression side in the mid-span region, as shown in Fig. 4a. With the increase of flexural load, wider cracks occur throughout the specimen width in the tension side (Fig. 4b), and severe concrete crushing in the compression side (Fig. 4c). Moreover, due to the superior adhesive bond between textile and concrete, most TRC specimens exhibited the desired flexural failure with large deflections.

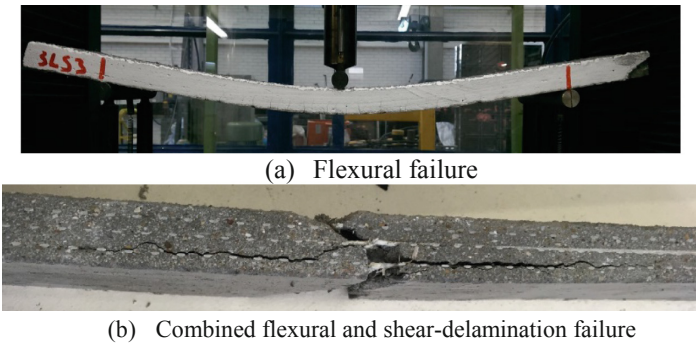


Fig. 3. Representative failure modes.

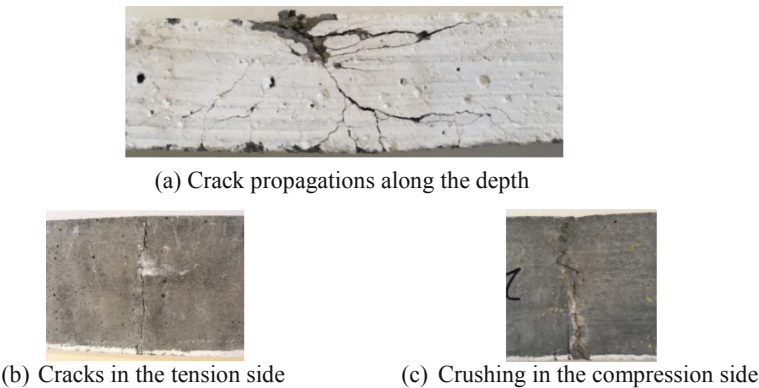


Fig. 4. Representative localized failure patterns

3.3 Nominal Flexural Stress-Strain Behaviours

The detailed test data, including the peak flexural load P , nominal flexural strength f and the nominal flexural strain ε at f , are summarized in Table 4. In this section, the nominal flexural stress and nominal flexural strain are calculated according to the Euler-Bernoulli theory for each specimen by considering the actual specimen size. The nominal flexural stress-strain responses for the cast and printed TRC specimens are shown in Fig. 5 and Fig. 6, respectively. Typical bi-linear flexural stress-strain curves are observed for all the TRC specimens. The curves exhibit two stages.

In the first stage, a linear elastic response occurs until the first cracking of concrete. At this stage, the contribution from the textile to resist the flexural load is insignificant since the flexural deflection of the specimen is very small and thus the tensile contribution from the textile is negligible. Therefore, the flexural stiffnesses at this initial stage are almost identical for the specimens with different layers of textiles. In the second stage, the specimens experience multiple tensile cracking as well as concrete crushing that leads to a decrease in flexural stiffness.

Table 4. Summary of the flexural test results.

Specimen	P (N)	P_{ave} (N)	f (MPa)	f_{ave} (MPa)	ε (%)	ε_{ave} (%)
C-L1-1	2477.4	2454.8 (0.07)	32.1	31.9 (0.07)	1.79	1.68 (0.05)
C-L1-2	2482.2		32.2		1.63	
C-L1-3	2213.2		28.7		1.63	
C-L1-4	2646.4		34.3		1.67	
C-L2-1	3877.2	3752.3 (0.05)	42.1	40.8 (0.05)	1.85	1.71 (0.08)
C-L2-2	3691.2		40.1		1.71	
C-L2-3	3529.2		38.3		1.51	
C-L2-4	3911.5		42.5		1.77	
C-L3-1	3040.0	3171.2 (0.03)	41.4	42.1 (0.04)	1.69	1.74 (0.02)
C-L3-2	3196.4		43.5		1.72	
C-L3-3	3191.9		43.4		1.78	
C-L3-4	3256.5		40.3		1.77	
P-L1-1	1976.7	2044.1 (0.05)	29.6	30.6 (0.05)	1.63	1.70 (0.06)
P-L1-2	2160.7		32.4		1.81	
P-L1-3	1995.0		29.9		1.65	
P-L2-1	2611.9	2760.6 (0.06)	39.2	41.4 (0.06)	1.76	1.84 (0.05)
P-L2-2	2739.9		41.1		1.83	
P-L2-3	2929.9		43.9		1.94	
P-L3-1	2654.1	2822.0 (0.06)	39.8	42.3 (0.05)	1.49	1.68 (0.10)
P-L3-2	2849.1		42.7		1.74	
P-L3-3	2962.8		44.3		1.82	

Note: P indicates the flexural load; P_{ave} indicates the average flexural load; f indicates the nominal flexural strength; f_{ave} indicates the nominal flexural strength; ε indicates the nominal flexural strain at f ; and ε_{ave} indicates the average nominal flexural strain at f . Coefficient of variations (CoVs) are calculated as included in the brackets.

The flexural performance of cast and printed specimens can be enhanced by increasing the layers of textiles, and the improvement between one layer and two layers is significant, but smaller between two and three layers. This difference is due to the location of each layer: at the rupture of the bottom layer, the tensile capacities of the middle and top layers are not fully utilized.

The flexural behaviour of the cast TRC specimens is more variable than their 3D printed counterparts (Table 4 and Figs. 5 and 6). One possible reason is that the textile positions and concrete layer thicknesses of cast specimens vary more than the uniformly printed counterparts, due to the method of securing each layer of textile at the sides of the moulds. As shown in Fig. 2, the thickness of the 2-layer cast specimen depth was significantly higher than the printed counterpart.

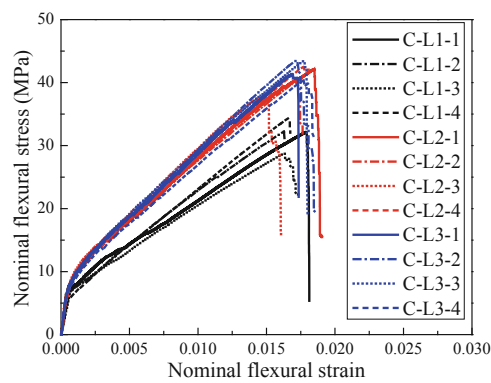


Fig. 5. Flexural behaviour of cast TRC specimens.

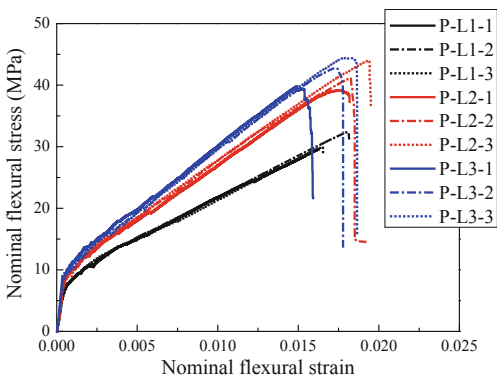


Fig. 6. Flexural behaviour of printed TRC specimens.

Direct comparisons of the cast and printed TRC specimens are shown in Fig. 7. It is encouraging to observe that the 3D printed TRC specimens have very similar flexural responses to the cast equivalents in terms of nominal flexural strength, flexural stiffness

and post-cracking ductility, indicating that the printing process does not result in significant detrimental effects compared to the conventionally cast equivalent. The test results of printed TRC specimens show high consistency (Fig. 7 and Table 4), which might be due to the precise digitally controlled printing process.

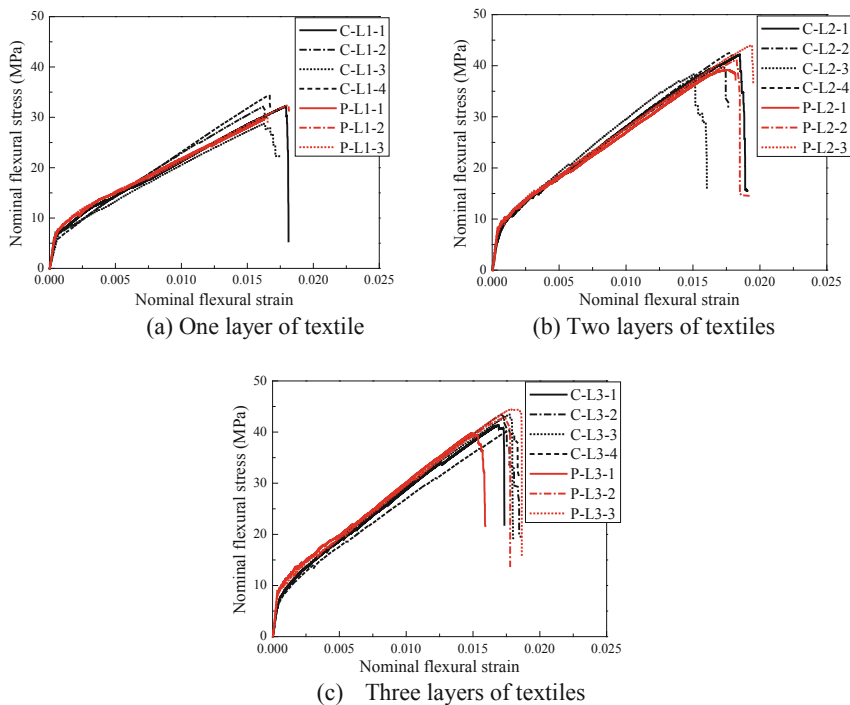


Fig. 7. Comparison of the cast and printed TRC specimens

4 Conclusions

This study aimed to investigate the use of AR-glass textile as the reinforcement of 3D printed concrete. To validate this strategy, cast and printed thin-shelled beam specimens were prepared with one to three layers of textiles. The specimens were tested in flexure under three-point loading. Based on the test results, the following conclusions can be made:

1. The textile reinforced concrete (TRC) specimens exhibit satisfactory flexural behaviours under three-point loading with significant strength and post-cracking ductility. The textile location affects the flexural behaviour of cast and printed TRC specimens: the bottom layer of textile provides the highest tensile resistance, followed by the middle and top layers of textiles.

2. 3D printed TRC specimens have very similar responses to the equivalent cast TRC specimens in terms of nominal flexural strength, flexural stiffness and post-cracking ductility, indicating that there aren't any detrimental effects related to the printing process.
3. The flexural behaviours of printed TRC specimens exhibit lower scatter than the cast TRC specimens, which is probably due to the precise digitally controlled printing process.

Based on these preliminary test results, future research should be conducted on the theoretical modelling of the flexural behaviour of printed TRC specimens as well as manufacture of textile reinforcement for more complex 3D printed concrete structures. Moreover, research on the automated textile placement method should be a priority.

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Digital design, Technologies and Industrialization



3D Concrete Printing - Free Form Geometries with Improved Ductility and Strength

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Abstract. Additive manufacturing (AM) or 3D printing is a rapid prototyping process that has captured the attention of architects and designers worldwide in the last few years. Multiple research groups and commercial entities are exploring different areas of 3D concrete printing (3DCP) with one of the main topics being the potential to improve the design freedom, while simultaneously achieving sufficient structural ductility. Based on the target design impression of a free form 3DCP structure, this study presents a number of 3DCP strategies to print arbitrary double-curved geometries with improved concrete ductility. A digital design-to-fabrication workflow was applied, consisting of defining parameters at various stages of the process. Two case study objects have been printed, both featuring double-curved surfaces achieved through cantilevered printing with support material, and by printing on a curved support surface, respectively. The former object acted as support for the latter. Entrained cables and secondarily added glass fibres were used to obtain ductility. The result is a double-curved 1×1 m panel with fibre-reinforced printed concrete, as well as a double curved print bed, reinforced with high strength steel cables.

Keywords: Fabrication and robotics craft · Robotic production · 3D concrete printing

1 Introduction

Additive manufacturing (AM) or 3D printing is a rapid prototyping process that has captured the attention of architects and designers worldwide in the last few years. It has allowed designers and architects to realize digital designs into tangible objects (Bogue 2013). 3D printing has emerged as a truly disruptive technology of the 21st century which could drastically affect many manufacturing industries (Labonnote et al. 2016). The initial application of 3D printing in the field of architecture was for producing conceptual models to study design flaws and illustrating the final design models (Khoshnevis 1999). Today, the application of AM in architecture and construction has changed to manufacturing structural and non-structural elements by printing with concrete, steel, and other building materials.

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F. P. Bos et al. (Eds.): DC 2020, RILEM Bookseries 28, pp. 741–756, 2020.

https://doi.org/10.1007/978-3-030-49916-7_74

Concrete being cheap and readily available worldwide, with high strength, durability, fire-resistance and ability to be mould into any shape in its fluid state, makes it can an attractive material to apply for AM in construction. The most commonly adopted system for Additive Manufacturing of Concrete (AMoC) is based on an extrusion-type process, which was first developed by Khoshnevis and termed Contour Crafting (Khoshnevis 1999). Based on this approach, various research groups and start-up companies began to explore the degree of design freedom, as one of the potentials for the 3D concrete printing (3DCP) technology.

However, concrete as a material has its limitations, with a ratio of approximately 10:1, concrete has a relatively high compressive strength while being weak in tension. Furthermore, its failure behaviour can be characterized as brittle, i.e., without any meaningful plasticity. In conventional concrete structures, steel reinforcement bars are applied to overcome this issue, but this common strategy is generally not compatible with 3DCP processes. The application of 3DCP has been mainly limited to designs that are stressed only in compression (Salet et al. 2017). This restriction can only partially be overcome through strategies such as printing along stress lines as these stress lines still have to be compressive (Yongqiang and Chen 2010; Tam et al. 2016).

Another constraint of most current extrusion-based 3DCP processes is that, unlike standard desktop extrusion printers, they lack the option to apply temporary support structures that can be used to print cantilevering subsequent layers (i.e., layers not centrally stacked on each other). This limits the geometrical freedom significantly. Therefore, alternative approaches must be considered to improve the degree of design freedom for 3D printable objects.

2 Research Goal

To enhance the possibilities of extrusion-based 3DCP, strategies need to be devised that further increase the design freedom while simultaneously achieving sufficient ductility to achieve structural integrity. An arbitrary double-curved structure presented in Fig. 1 has been taken as a target application to showcase the generic nature of the strategy. This research aims to develop and apply 3DCP strategies that would allow its realization. A digital design-to-fabrication workflow was applied, consisting of defining parameters at various stages of the process.

Two case study objects were printed. In the first, a double-curved surface is achieved by printing cantilevering filaments that are supported during printing with a granular, temporary support material that can easily be added, removed and re-used. A previously developed method to entrain a reinforcement cable with the concrete filament was applied to obtain ductility (Bos et al. 2017). The second object, representing an actual part of the wall design, was printed on the double curved surface of the former. The print mortar was reinforced with fibres that were added to the mixture at the print head. The result is a double-curved 1×1 m panel, as well as a double curved print bed.

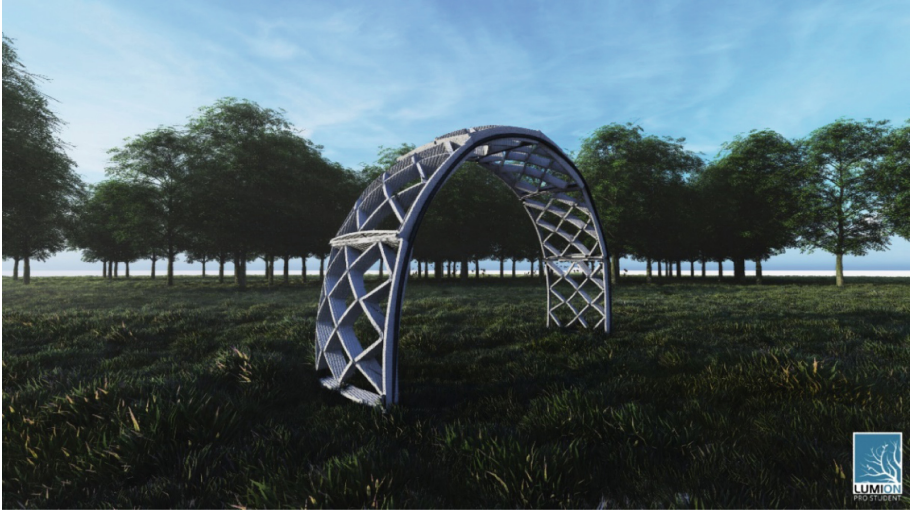


Fig. 1. Architectural concept design of a double-curved free-standing wall. Realization through 3DCP requires the development of a strategy both for the geometry and for the ductility.

3 Digital Workflow

A double-curved panel and its double-curved printed bed were designed using Grasshopper 3D, by following several design steps. The aim was to create a script that can automatically change the dimension of the print bed and the pattern of the panel depending on the required parameters for the panel, such as curvature angle, length, and width. The script also considers the requirements of the robot, such as the printed-element dimensions, the possible curvature angle printable using a gantry robot and the nozzle dimensions for the corner radius.

The script is composed of different parts. First, a double-curved surface was generated. For this specific experiment, it was generated by cutting a sphere (Fig. 2a), but also different double curved surface can be applied. The double-curved surface is characterized by a curvature angle of less than 20° (Fig. 2b). The limitation on the angle was based on the data from the previous printing experiments on double curve surface for printing the shell (Borg Costanzi et al. 2018). A higher inclination resulted in layers sliding off of each other or the print surface. The double-curved surface is then used as a starting surface to build the print bed. Secondly, the surface is extended towards a rectangular outer-perimeter (Fig. 2c). Following this procedure, a surface that corresponds to the target surface is obtained (Fig. 2d).

The 2D curved surface is made “printable” by transforming it into a 3D geometry. This is achieved by generating a box which base is the perimeter of the 2D curved surface. The resulting form is characterized by the upper side containing a double-curved surface (Fig. 3a) with the following dimensions: 1400 mm

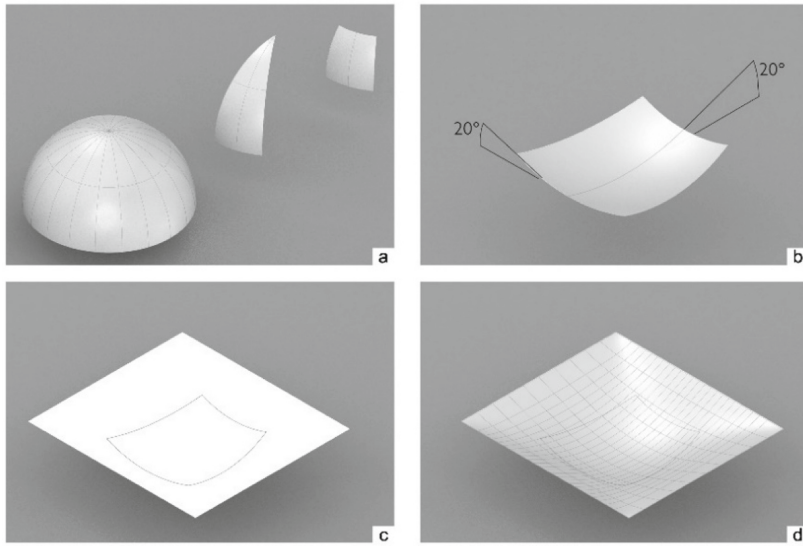


Fig. 2. (a) Development of the double-curved surface, which is generated by slicing a sphere's geometry. (b) The “sliced” surface from the sphere geometry, which is composed of a 20° curvature both vertically and horizontally. (c) Basic geometry used to create the surface of the print bed. (d) The boundaries of the double-curved shape and the rectangular perimeter create a double-curved mesh.

length $\times$ 1290 mm width $\times$ 400 mm height. To make the box 3D-printable, it is sliced into four pieces (Fig. 3b). To ensure the stability of the shape, an inner pattern is created. Lastly, the algorithm ensures that the corners of the shape have a minimum radius that is equal to the dimension of the nozzle (60 mm) (Fig. 3c) as a smaller radius results in excessive local material deposition.

A “woven” pattern was chosen for the double-curved surface as it allows the creation of an internal “net” within the design for both open and closed areas. Moreover, the “woven” pattern allows for multiple points of contact along the pattern, providing a more stable design (Fig. 3d).

The pattern was created by weaving together alternating points along the surface, which were extrapolated by the isocurve of the surface. An outer perimeter is added to the pattern that follows the outer edge of the panel, improving stability.

Figure 4 shows the centre-line of the print path. The minimum distance between two lines, to ensure contact between them, is equal to the nozzle width. The curvature radius of the pattern also corresponds to the dimensions of the nozzle. The final digital model of the geometries were sliced and converted to G-code using a Rhino Grasshopper based script to create toolpaths for printing.

4 Experimental Setup

The 3D concrete printing process adopted for this research is an extrusion-based process, which places filaments of concrete layer by layer with 4-degrees of freedom with a gantry robot, in a print area with a maximum size of $9 \times 4.5 \times 2.8$ m. It uses a 1-component dry mortar that is mixed with water and pumped to the print nozzle with an M-Tec Duomix 2000 mixer-pump through a 25.4 mm diameter rubber hose of 10 m length. The capabilities and limitations of the system have previously been extensively described (Bos et al. 2016).

For both objects, Weber 3D 145-2 mortar was used. The printability and hardened properties have been studied previously (Wolfs et al. 2018a; 2018b, 2019). In the support object, the standard water-to-dry mix ratio of 0.144 was applied. However, the water-to-dry mix ratio in the second printed façade panel object was 0.149, due to the use of fibres and the resultant workability loss.

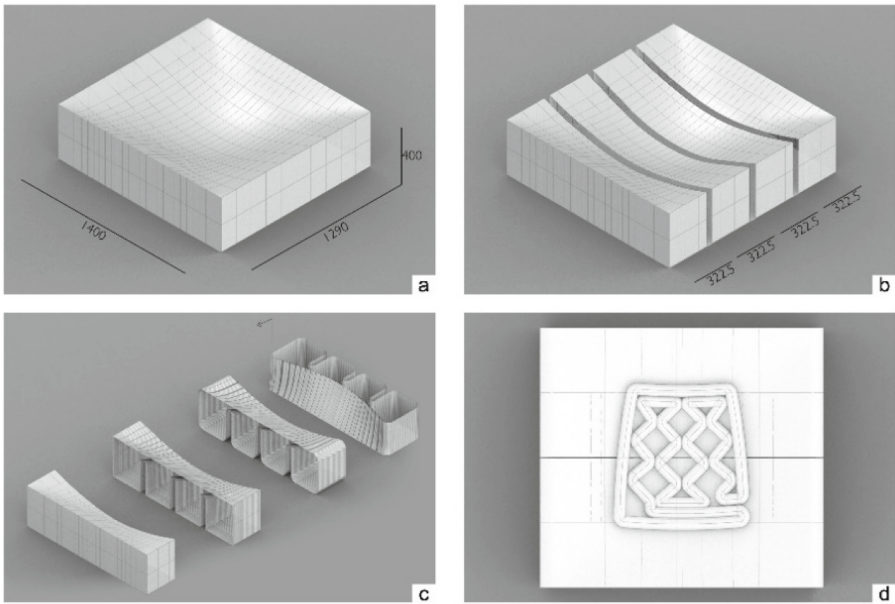


Fig. 3. (a) Dimensions of the print bed for the double-curved panel. (b) Subdivision of the print bed, so it can be 3D-printed. (c) Internal view of one section of the print bed. The internal pattern is created to provide more stability. (d) The double-curved surface is characterized by a “woven” pattern that ensures frequent areas of contact between the inner structure and the outer perimeter.

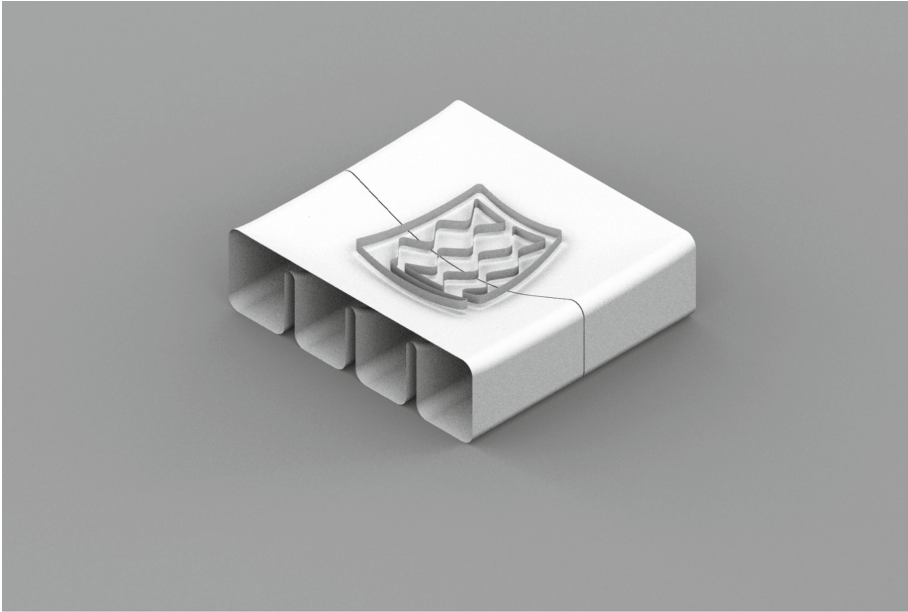


Fig. 4. The pattern's geometry has the same curvature as the print bed.

5 Strategies for Double Curvature

5.1 Printing with a Granular Support Material

To achieve design freedom for printing objects which can have a cantilever, experiments were conducted to develop a strategy to improve the bearing capacity of the support material without influencing the printed concrete. The first series of trial printings tests were performed to determine a suitable support material. To achieve this, different materials like kitchen salt (Fig. 5a), sand (Fig. 5b) and lightweight expanded glass aggregates (Fig. 5c) were explored. Based on availability and robustness, the lightweight expanded glass aggregates were finally used as the temporary support material.

Subsequently, an experiment was performed to establish the maximum achievable angle of cantilevering (Fig. 6). This was done by printing an arbitrary object of 453.3 mm height and 773.90 mm in diameter, with increasingly steep cantilevering angles (shown in Fig. 6b, the subsequent angles were 57.3°, 48.4°, 38.8°, and 21.9° with the horizontal). The object was printed with a 40 × 10 mm nozzle opening inside so that support material could be applied on both sides of the object. The experiment showed that the maximum cantilevering angle which could be achieved was approximately 30–40° (Fig. 6c) with lower angles the layers could not be adequately placed without affecting the bond between the layers (Fig. 6a).



Fig. 5. Example of supporting material: (a) Concrete printing with salt as supporting material (Retsin and Garcia 2016). (b) Sand as supporting material (Salet et al. 2017). (c) Lightweight granular aggregate.

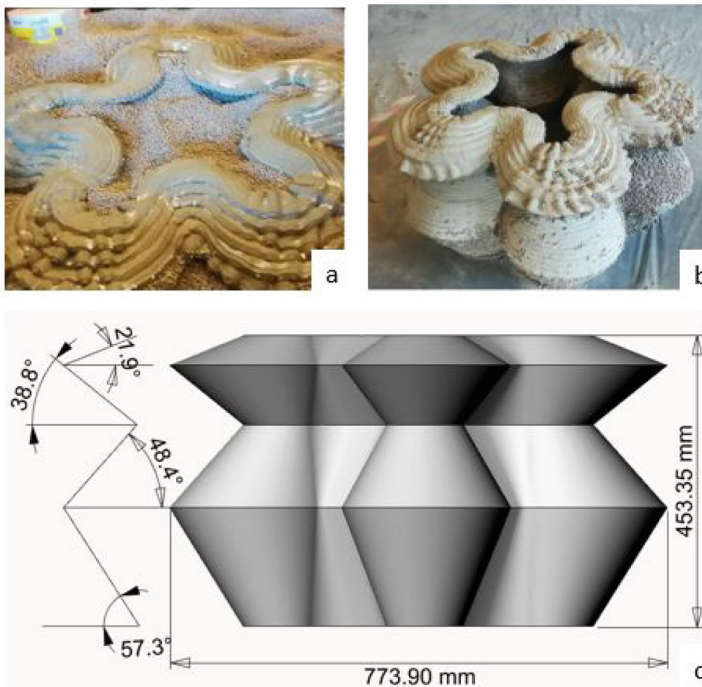


Fig. 6. Results from testing the support material.

A final print test focused on improving the system by printing without a confinement box. This was done by using the printed object itself to confine the supporting infill material. A conical object with 400 mm in height, 500 mm in bottom diameter and 250 mm in top diameter (cantilevering angle 64°) was printed without failure, thus validating the concept (Fig. 7).



Fig. 7. Example of printing process without a confinement box.

5.2 Printing on a Double-Curved Surface

Increasing the form freedom of 3DCP by printing on a (double) curved surfaces has been previously performed (Borg Costanzi et al. 2018; Lim et al. 2016; Tam et al. 2016). Some of the issues to be considered, which have been identified in these studies include:

- The maximum angle of inclination before layers slide of the print surface or each other.
- The effects of a print nozzle not being perpendicular to the print surface due to a lack of sufficient DoFs of the robot.
- The localization of the print nozzle respective to the print surface.
- The material and fabrication of the print surface.

6 Strategies for Ductility

6.1 Reinforcement Cable

Currently, the problem of reinforcing digitally fabricated concrete has been recognized as one of the major issues to solve to allow a general breakthrough of these technologies (Salet et al. 2017). A range of different reinforcement strategies has been explored in academic studies and by commercial entities, as discussed to considerable extent by Asprone et al. (2018).

One of the strategies that have shown considerable potential is the automated entrainment of high strength steel cable in the concrete filament (Bos et al. 2017, 2018, 2020). A significant advantage is the fact that the cable can be applied concurrently with the deposition of concrete filament, i.e. no additional process steps are required. The potential of the concept has been confirmed by (Lim et al. 2016; Ma et al. 2019). In the current study, a Bekaert Syncrocord Force 0.6, with a diameter $d = 0.63 \text{ mm}$ and a yield load of 381 N has been applied in the first object (support object). It is extremely flexible, allowing it to follow the curved concrete filament. Even the 180 angles have been applied in the internal vertical supports in this object. The position of the reinforcement cable in the concrete is identical to the tool path (Fig. 10c).

6.2 Introduction of Fibres

Another strategy to obtain tensile strength and ductility in printed concrete is the addition of fibres to the matrix. Several researchers have explored this path, as shown in an overview by Wangler et al. (2019). An integration of 3D printing freeform complex geometries with fibre reinforced printed concrete has, to the knowledge of the authors, not yet been presented. The approach adopted in this research for introducing fibres into the printed concrete is through a simultaneous process of fibre deposition. A generic fibre reinforcement entrainment device (FRED) was used for introducing fibres into the printed layers, as shown in Fig. 8. Rather than incorporating fibres into the mortar before mixing in the mixer-pump, they have been added in a second step mixing unit at the print head. This method allows the use of a wider selection of fibres whereas the narrow cavities of the linear-displacement pump in the mixer-pump would only allow for very small fibres with limited structural effect. The detailed description of the device with the method of application has been elaborated in (Ahmed et al. 2020).

For this research glass fibres called CEM-FIL minibar 24 mm in length and a quantity of 58.9 kg/m^3 were used to improve the ductility of the printed panel. The double-curved façade element that was printed as the second object in this study was fibre reinforced. To determine the strength and ductility performance, a separate down-scaled Crack-Mouth Opening Displacement (CMOD) test was performed on the fibre reinforced material, according to the method previously described (Bos et al. 2019). The resulting CMOD-load diagram is shown in Fig. 9. With a residual strength ratio of approximately $f_{R,3}/f_{R,1} \ 0.8 - 1$, this combination is highly promising for structural applications even though further improvements in performance and production quality are required.



Fig. 8. Fibre reinforcement entrainment device (FRED) (Ahmed et al. 2020)

The double-curved façade element that was printed as the second object in this study was fibre reinforced. Rather than incorporating fibres into the mortar before mixing in the mixer-pump, they have been added in a second step mixing unit at the print head, through an innovative device that will be detailed in a future publication, and is based on a concept previously described (Bos et al. 2019). This method allows the use of a wider selection of fibres whereas the narrow cavities of the linear-displacement pump in the mixer-pump would only allow for very small fibres with limited structural effect. CEM-FIL 24mm fibres (Owens Corning 2019) were applied, in a quantity of 58.9 kg/m^3 . To determine the strength and ductility performance, a separate down-scaled Crack-Mouth Opening Displacement (CMOD) test was performed on the fibre reinforced material, according to the method previously described (Bos et al. 2019). The resulting CMOD-load diagram is shown in Fig. 9. With a residual strength ratio of approximately $f_{R,3}/f_{R,1} \ 0.8 - 1$, this combination is highly promising for structural applications even though further improvements in performance and production quality are required.

7 Printing Experiment

The final printing test consisted of two parts, each using a different strategy to achieve double curvature and ductility. The double-curvature was achieved through cantilevered printing with supporting material and ductility by the application of reinforcement cable. In the façade panel, double-curvature resulted from printing on the curved print-bed while ductility was achieved by applying fibres as described in Sect. 6.2.

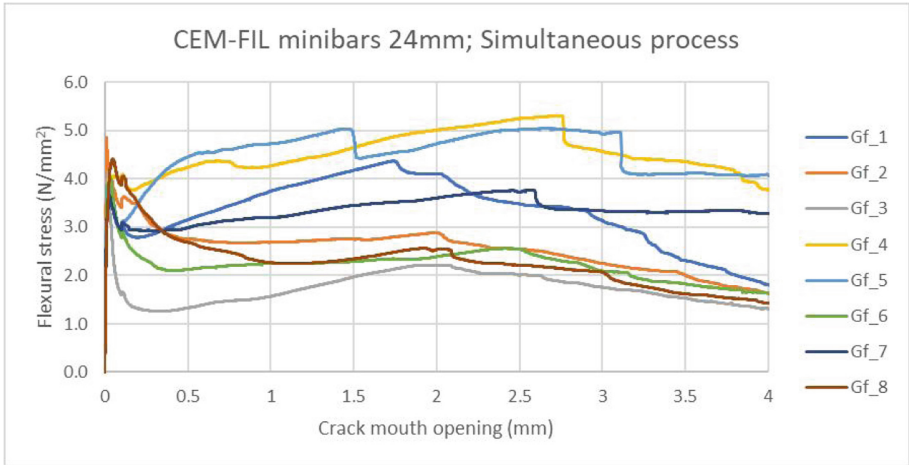


Fig. 9. Resulting CMOD-load diagram (Ahmed et al. 2020)

7.1 Double-Curved Support

The printed object was divided into four equal elements of 322 mm each along the width. This division was required because, since no containing box was used, outward cantilevering cannot be supported with the infill material, and, hence, the object must only cantilever inward during printing. A common failure mechanism in the fresh material state of 3DCP structures is buckling (Wolfs et al. 2018a; 2018b). However, since the interval for material deposition for consecutive layers is short, the object collapses during printing due to plastic failure (Fig. 10a).

Each element was printed and flipped by 90° before assembling (Fig. 10b) them as the printing process needs a flat print bed for supporting the deposited material. During assembling no additional material was used. The elements were leveled and placed next to each other.

The print nozzle used for this test was a hybrid-rectangular back/down flow nozzle with an opening dimension of 60×12 mm, as shown in Fig. 11. When reinforcement cable is used, the orientation of the flow of concrete filament requires particular attention. Research has shown that a vertical down flow results in the slicing of the filament by the cable while a horizontal backflow leads to a drastic reduction in layer adhesion (Salet et al. 2018).

To maintain a uniform layer dimension, the experiment was conducted with a print speed of 100 cm/s and an extrusion rate of 3.6 l/min. Layer offset between consecutive layers was 10.5 mm in height therefore each element comprised of 31 layers. Once the printing was completed, all the elements were sprayed with a curing agent (BMP Curing Compound AC) and wrapped with a plastic foil to avoid dehydration.

The experiment showed that the use of an infill material significantly improved the capabilities of 3DCP to print freeform geometries (Fig. 10c). Particularly for larger sized parts, the method is highly compatible with the use of automatically entrained reinforcement cables. However, the deposition of support material needs to be automated and synchronized with the deposition of the printed layers to be implementable in a large scale 3DCP application.

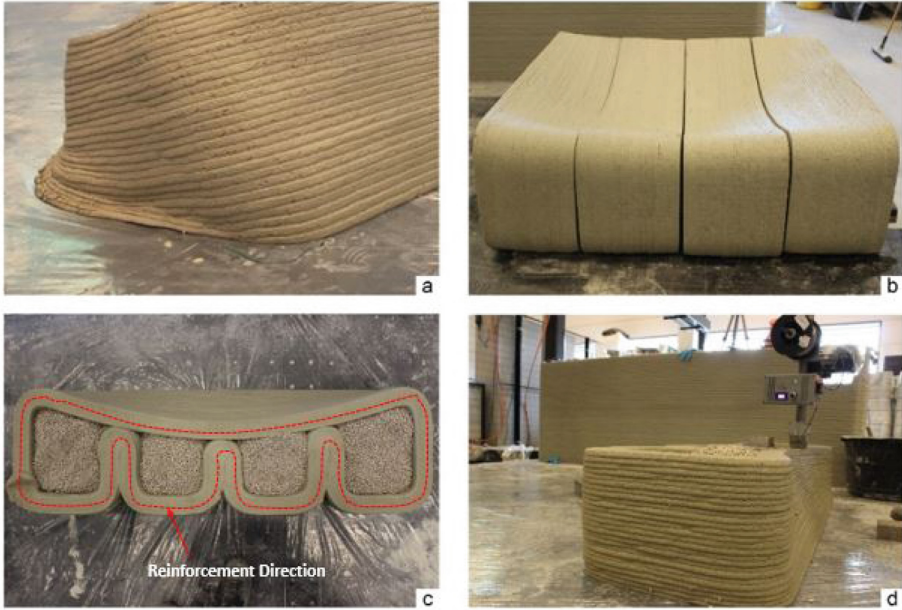


Fig. 10. (a) Effect of plastic failure during the printing process. (b) Subdivision of the print bed. (c) The inner pattern of the printed bed. (d) Reinforcement entrainment device (RED) during the printing process.

7.2 Double Curved Façade Panel

In the digital workflow for designing the print bed and panel, the dimension and curvature of the panel were based on the print bed and the overall base geometry from which it was generated. The other governing factor influencing the design considerations of the panel was mainly based on printing limitations. Due to considerations detailed in Sect. 3, the angle of the surface with the horizontal was limited to a maximum of 20° . Printing on a curved surface prohibited the use of reinforcement cable, as the required nozzle is geometrically incompatible with the curved surface. It should also be mentioned that a circular nozzle opening is easier to use on a double curved print bed (albeit not strictly necessary).

As the device used for fibre addition can be combined with any type of nozzle (rectangular, circular, down- or backflowing), a circular down flow nozzle

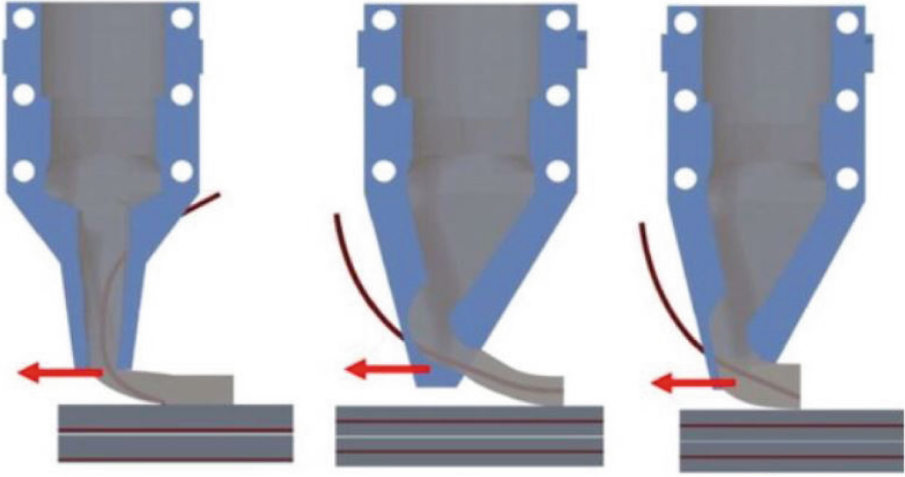


Fig. 11. Schematic showing the advantage for the hybrid nozzle for printing with cable reinforcement (Salet et al. 2018).

of 20 mm diameter was used. The print bed surface was covered with a foam sheet to obtain a smooth surface, covered with a plastic sheet to avoid the façade panel from adhering to the print bed.

Due to the smaller cross-section of the nozzle opening and the adjusted water-to-dry mix ratio (Sect. 4), the extrusion rate and the print speed needed to be re-synchronized. As a result, the print speed was increased to approximately 12 cm/s, and the extrusion rate was reduced to 2.8 l/min. As a circular nozzle was used to print the panel, the orientation of the nozzle was irrelevant. Thus, the rotational capacity of the print arm was not used. Due to the nozzle geometry, the allowable turning radius was also much smaller than for object 1, allowing for a more intricately designed panel (Fig. 12a). The layer offset for the initial layer was kept 10 mm from the curved print bed to produce layer dimensions of 40×10 mm. Similar to the printing of object 1, the panel was sprayed with a

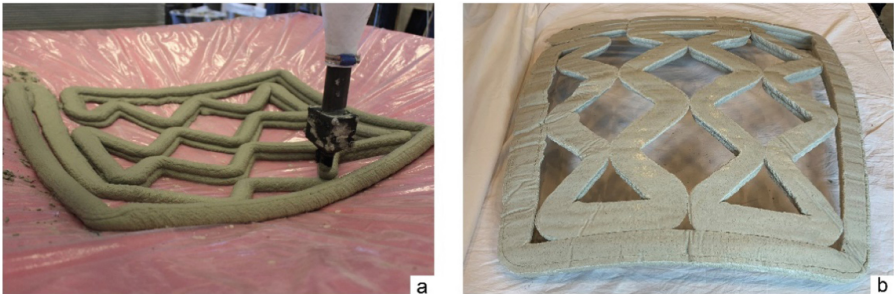


Fig. 12. (a) Printing inner geometry for the panel. (b) The final result of the double-curved panel.

curing agent (BMP Curing Compound AC) and wrapped with a plastic foil. It was allowed to cure and was left undisturbed in the print bed for 24 h before moving.

The printing process on the double curve print bed can be improved by printing with a 6-axis robotic arm as the nozzle can be always oriented perpendicular to the surface of the print bed (Fig. 13a) (Borg Costanzi et al. 2018). This could allow the use of reinforcement cable as well, which was not possible in the current experiment. However, printing on a curved surface is likely to stay limited to shell-type structures as increasing the number of layers will result in failure during printing due to the instability of the layers (Fig. 13b).

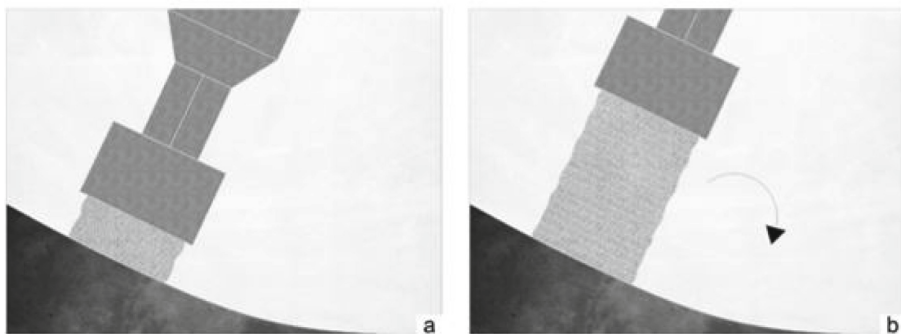


Fig. 13. (a) Printing using a 6-axis robotic arm, the material is placed perpendicular to the surface. (b) Failure during printing, due to the instability of the increasing number of layers.

8 Conclusions

Different strategies for achieving double curvature and ductility were used for both printed elements. Particular advantages of printing cantilevering layers with temporary support material and on a curved print bed were discussed. Their compatibility with the use of automatically entrained reinforcement cable and glass fibres were discussed. The resulting objects show that a double-curved 3D concrete printed structure is feasible through the use of the presented technologies.

Acknowledgements. The support of the staff of the Structures Laboratory Eindhoven is gratefully acknowledged. The support and guidance of Prof. ir. Juliette Bekkering, architect ir. Sjef van Hoof and, architect ir. Barbara Kuit is highly appreciated. The assistance in the 3DCP research of Master track students from Structural Design and graduation studio of Architectural Urban Design Engineering at the TU/e Department of the Built Environment is highly valued. For this paper, the authors appreciate the work of Remi Bogaert and Michael Yuen in particular, for their assistance in the experimental work. The TU/e research program on 3D Concrete Printing is co-funded by a partner group of enterprises and associations, that on the date of writing consisted

of (alphabetical order) Ballast Nedam, BAM Infraconsult bv, Bekaert, Concrete Valley, CRH, Cybe, Saint-Gobain Weber Beamix, SGS Intron, SKKB, Van Wijnen, Verhoeven Timmerfabriek, and Witteveen+Bos. Their support is gratefully acknowledged.

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Print-Cast Concrete: Additive Manufacturing for 3D Printing Mortar in Robotically Fabricated Green Sand Molds

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Abstract. The research investigates architectural-scale concrete 3D printing in robotically fabricated recyclable molds for the fabrication of rapidly constructed, structurally optimized, architectural-scale concrete structures. The research of *Print-Cast Concrete* utilizes a three-dimensional extrusion path for deposition of material over a subtractive shaped sub-structure of CNC tooled compacted green sand. This process expedites the production of doubly curved concrete geometries by replacing traditional formwork casting or horizontal corbeling with spatial concrete arching deposited in relation to optimized structural loads. Creating robust non-zero Gaussian curvature in concrete, this method increases speed over typical pre-cast concrete fabrication practices, especially when producing mass customized unique elements. Through the casting component of this method, concrete 3D prints have greater resolution along the edge condition resulting in tighter assembly tolerances between multiple aggregated components. Addressing digital form finding and optimization, material behaviors, and novel utilization of robotic fabrication, this research work displays a series of key concepts within *Print-Cast Concrete*, advancing edge condition precision of extrusion-based 3DCP.

1 Intro and Context

Advancements in additive manufacturing technology have provided the tools to rapidly produce unique forms, shifting from mass production to mass customization [1]. Concrete as a viscous material with numerous fresh and hardened state properties, historically has relied on the use of various types of molds for both cast in place construction along with pre-cast construction techniques [2]. Having the benefits of manufacturing precision, pre-cast concrete as an industry can mass produce concrete elements such as wall sections, columns, and beams repeatably. With cast-in-place concrete, curing times can slow down the speed of construction. The production of customized geometries leads to wasteful one-off molds and formwork. Pre-cast concrete fabrication uses the same mold multiple times, eliminating the potential for mass customization. Integrating the design of precise edge conditions into the casting process allows for concrete elements to interlock during on site construction [3]. With advancements in architectural fabrication through digital techniques and robotics, 3D

Concrete Printing has been seen and tested as a possible alternative to concrete cast in place construction. Recent developments in additive manufacturing, along with material science make it possible to construct building components directly through material deposition eliminating any formwork. Research such as Contour Crafting by Behrokh Khoshnevis of USC [4], TU Endhoven's 3DCP programme [5], or XtreeE [6], explores concrete 3D printing as a deposition of two-dimensional layers for the creation of three-dimensional form. Using corbeling, various layers can shift no more than half the width of the previous layer below, resulting in curvature of three-dimensional form [7, 8]. A time consuming process which has both impact on the types of geometry that can be created and the potential for additional printing of support material, corbeling also produces striated edge conditions that do not allow for multiple printed objects to seamlessly connect to one another depending on their resolution. Here, we see concrete 3D printed components result in stereotomic monolithic constructions based on their material and print resolution.

In looking at the precision seen in the pre-cast construction industry and the ability to cast edge conditions for onsite construction, the research of *Print-Cast Concrete* looks at the fabrication of mass customized concrete 3D printed elements exhibiting double curvature and precise edge conditions. Embedding the construction and assembly logic into the design of the pre-cast components allows for speed and efficiency both within the fabrication facility and on the construction site. By combining the advantages of 3D printing with precise material deposition, material efficiency, and integration of structural analysis with robotic toolpath, *Print-Cast Concrete* removes the imprecision of typical concrete 3D printed corbeled edge conditions and replaces it with the precision of cast edge conditions. With previous research publications of *Sub-Additive Manufacturing* [9] to create concrete components with double curvature, and *Rough-Pass Extrusion Tooling* [10] for the post processing of edge conditions of concrete 3D printed elements, *Print-Cast Concrete* looks to combine the successful characteristics of both, and implement them into the forefront of the fabrication process.

2 Methodology

Building off the research developed as part of *Sub-Additive Manufacturing*, *Print-Cast Concrete* utilizes a low-cost reusable aggregate and the technique of sand forming for the development of self-supporting curvilinear surfaces as casting mediums. With the Philips Pavilion at the Brussels Expo of '58 [11], Le Corbusier used hyperbolic sand forms to cast concrete panels to achieve both curvature and material surface. By placing formwork with precise edges onto the sand dividing the panels, parabolic reinforced concrete components were cast on the manipulatable surface ensuring precision during on site construction.

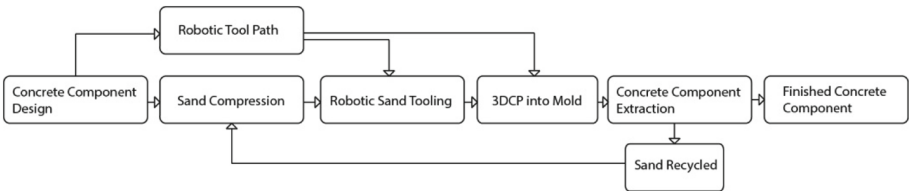


Fig. 1. Fabrication process diagram for *Print-Cast Concrete* concept

The Print Cast Concrete Concept. In exploring the intersection of mass customization, rapid manufacturing techniques, concrete 3D printing, and pre-cast construction, this research developed a process of robotic fabrication combining both CNC robotic milling and concrete material deposition. Looking at low-cost reusable aggregate formwork, a green sand mixture was utilized for the creation of bespoke molds. The utilization of green sand as a mold material for casting has been used extensively in the automotive and metals manufacturing industries. Used in the casting of molten metal and glass sand molds, green sand can resist materials with high temperatures and retain resolution when making molds of intricate geometries [12]. Oil sands have been used in robotic experimentation for wall panel casting in the Gramazio and Kohler research lab as part of their project *Procedural Landscapes 2* [13]. The green sand is utilized for the fabrication of the *Print-Cast* molds as it is inexpensive to produce in large quantities, can be CNC tooled at high speeds, and can be recycled, remolded, and reshaped with little effort. The addition of a small percentage of water to re-hydrate the mixture returns the sand to a material state where it can be cast and molded or transported and stored as a dry material. The green sand mixture contains a mix ratio of 9:1 Fine Kiln Dried Sand to Bentonite Clay Powder. Water is added to the mix until the sand becomes damp and hydrated, enough to be compacted to hold precise geometrical shape. Here, it can be stored in airtight containers for up to 2 months before needing to be re-hydrated.

Once the sand mixture is formed, it is deposited into standard rectangular low-profile boxes and compacted into a hardened solid. The research team performed this process using a 25 cm hand tamper tool, with aspirations of developing a hydraulic press to increase the speed of the sand compression procedure. Employing a Kuka kr60 with krc4 controller, the robotic platform was equipped with air pneumatic valves and a multi-tool changer to switch between various end effectors at multiple during fabrication. With the green sand blank in place, the 7457w CNC spindle along with a 19 mm diameter 15 cm 4 flute end mill is engaged on the robotic arm. Milling at $\frac{1}{2}$ m/s the robot first performed a roughing pass to remove most of the green sand material parallel to the sand mold utilizing typical 3 axis milling toolpaths. After the rough pass was completed a finishing toolpath was developed unique to the geometry and edge condition for each *Print-Cast Panel*. Utilizing all 6 robotic axes, the sand mixture was strong enough to perform undercut milling geometries into the side wall of the sand forms, proving the concept of precise interlocking male to female edges were capable to be implemented into the design process. With green sand tooling, geometries were now possible to be implemented within the concrete casting process without the use of resin bonding agents in the sand, have high degrees of geometrical resolution, and low material cost associated with this process. After the completion of the subtractive fabrication of the sand mold, extracted sand was utilized for the casting of additional sand blanks in the production process (Fig. 2).



Fig. 2. Green sand molds robotically CNC tooled and prepared for concrete extrusion.

With the sand mold processed, the material deposition of 3D printable mortar can begin. Switching end effectors from the CNC spindle to the concrete extrusion end effector, 3D printable mortar is weighed and mixed in relation to the toolpath generated for the *Print-Cast Panel*. Partnering with LATICRETE International, Inc, 3D printing mortar was developed that exhibited an open extrusion time between 45 min-1 h, could deposit and stack 9 mm layers consistently, and had a load bearing capacity of 29.2 MPa's after a curing period of 28 days. The combined 3DCP mortar was deposited into the hopper of a piston style mortar pump via a 2.5 cm diameter hose to the end effector on the end of the robotic arm. The concrete extrusion end effector consisted of a material hopper and auger driven by a NEMA 23 stepper motor. Material was then deposited into the sand mold in 9 mm layers in coordination with the toolpath. Over extrusion was utilized along the sand mold edges to press the material against the mold and cast into the undercuts and precise edge geometry necessary for panel to panel connections. Halfway through printing, a prefabricated rebar frame was placed into the concrete panel, and then additional mortar was extruded per the fabrication of the panel geometry. Once the mortar material is dynamically cast into the sand mold, it can be transported to a location to cure while additional panels are robotically casted. After 24 h, the panel is extracted from the sand mold, cleaned, and set aside to continue curing for 28 days at a temperature of on average 70 °F and relative humidity of 70% as the fabrication space was not a condition controlled space. The sand is remolded into its compressed blank and is ready to be re-tooled for further geometries (Fig. 3).

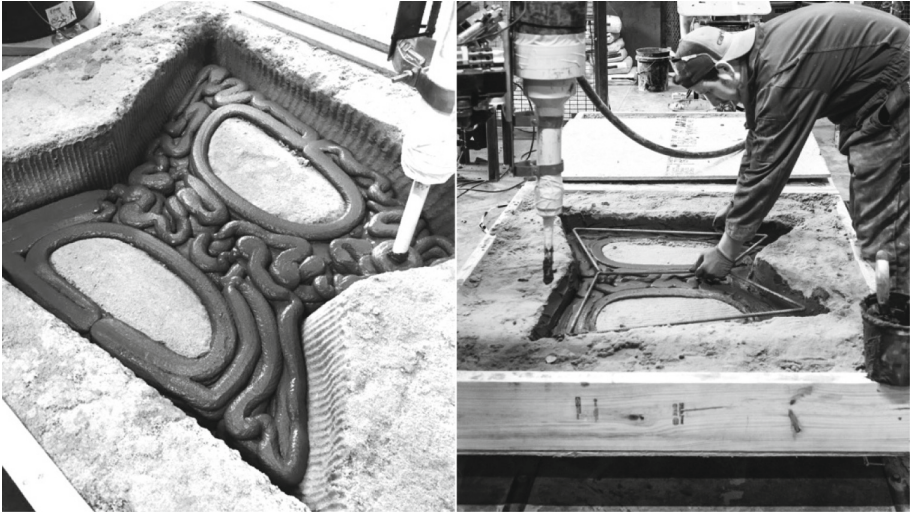


Fig. 3. Growth algorithm extrusion tool path and rebar placement into panel geometry.

The closed loop recyclable process of tooling green sand allows for the mass customization of bespoke molds necessary for the creation of precise edge conditions in 3D printing while also maximizing sand recovery. Losing less than .25% of sand to absorption into the 3DCP's first layer during the extrusion process, a finite volume of sand can produce a multitude of molding geometries that is cost effective and materially efficient. Interior mold edges with precise male and female undercut geometries can be casted along the edge of 3DCP geometry without post processing techniques.

3 Structural Optimization and Workflow Strategy

3.1 Robotic Fabrication and Manufacturing Simulation

The process of *Print-Cast Concrete* was developed in conjunction with necessity to produce a full-scale architectural installation commissioned for the bi-annual event *Exhibit Columbus* in Columbus, Indiana, USA. The proposal was to design and fabricate a concrete 3D printed compression shell, spanning 12 m in length, 5 m in width, and 3 m in height, with 4 parabolic arches allowing entry into the proposed project. Consisting of 110 bespoke panels ranging in weight of 45 kg to 160 kg per panel, totaling 9100 kg. Using this production method, the project would have the ability to be assembled and disassembled within the timeframe of the temporary outdoor exhibit, produced <1% of mortar material waste in the casting of the concrete components, and used 60% less material than if it were to be cast in place on site using traditional methods (Fig. 4).

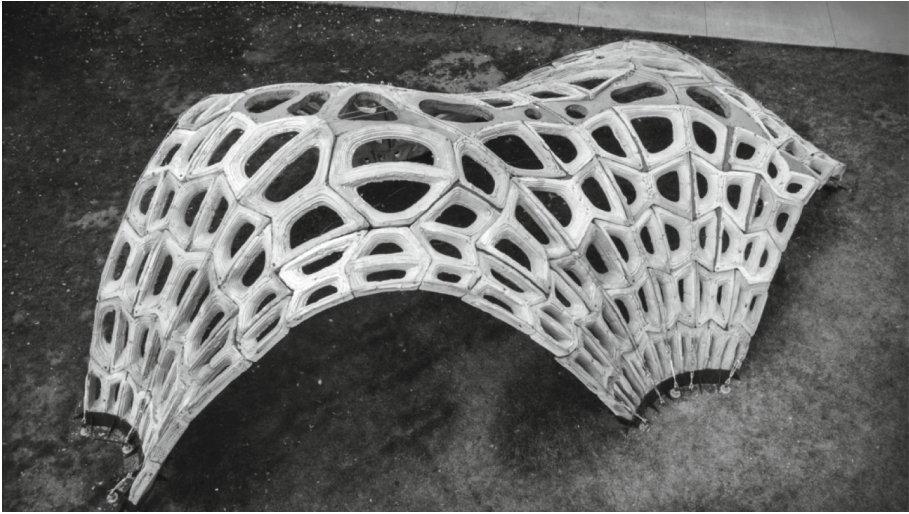


Fig. 4. DE|Stress Pavilion fabricated from Print Cast Concrete method for Exhibit Columbus.

The production cycle for this project was a timeframe of 2 months, from when mortar material arrived at the robotic lab facility to the shipping date for onsite installation. Without access to a linear rail for the Kuka kr60 platform or assembly line to move compressed sand blanks, the fabrication team developed a system of moveable sand mold blanks that could be locked in place within the robotic cage, milled, cast, then transported to a location for curing outside of the fabrication space. Ranging in size and scale in coordination with panel size generation, each sand mold blank held a minimum of 300 kg of sand with the largest blanks holding upwards of 900 kg. Simulating a manufacturing process larger than the scale of the university lab 4–6 unique panels were produced on average per day with a two-person fabrication crew, a process that would not have been possible at this pace using traditional concrete fabrication techniques. Future developments envision a two robotic setup and assembly line in a linear organization where molds are first tooled, then are transported to be extruded with material, before curing and ultimately being extracted.

3.2 Design Optimization in Evolutionary Form Finding

Looking at pure compression structures, the research into the possible application of *Print-Cast Concrete* centered around shell design and typology. Having the commission to design, fabricate, and construct a full-scale pavilion using this method, the design of the concrete shell was tasked to respond both to material, form, site, and context within the scope of the overall exhibition. Using evolutionary solvers, the parameters of the shell was to touch down to the ground plane at 4 locations with curvilinear radiuses. The resulting parabolic arches of various heights created the openings into the structure that responded to both compression forces and site conditions. Arch apex's were the following, 2.8 m, 2.4 m, 1.2 m, 1 m. Structural analysis integrated into compression form finding algorithms produced the curvature within the form of the overall geometry

placing the project in a state of pure compression. Since the installation was temporary, 6.35 mm steel cabling and tension rods located in the steel foundation spanned over the exterior of the shell placing additional compression forces on the arches and spans. The addition of this force load was to ensure that the acting force of an unexpected live load would not shift the structural integrity of the project.

The overall geometry was then subdivided into 110 bespoke panels, whose constraints were determined by the bounding box geometries of the compressed sand mold blanks and reach of the Kuka kr60 robotic platform. Form generation for these panels looked at interlocking geometries that both top and bottom panel components when placed into compression would interlock the two panels placed in between. Formally resembling a bow tie, the edge seams between panels would not span across multiple rows of individual geometry. Panel sub-divisions and openings within each of the panel geometries corresponded to both the force loads moving through the structure, resulting in the reduction of weight and material usage. The design of the pavilion ranges in material thickness from 20 cm to 10 cm and due to its unique fabrication, has a material texture on the interior depicting the act of casting, and on the exterior layering expressing its extrusion. The project's ornamentation expressing how it was made.

Using the sand mold to contain the edge conditions of each panel geometry, the *Print-Cast* technique allows for precise geometry along the edges not found in traditional concrete printing strategies. To increase the pavilion's resistance to shear forces, interlocking nesting geometries are integrated into each edge condition of the panels. Not exceeding .785 rad of undercut, the CNC spindle end effector on the robotic platform tools out the male and female sand geometry, and over extruding during the printing process casts the undulating surface with accuracy and tolerance that cannot be achieved through corbeling at this scale. When nested together, the edge condition informs both the construction logic and feedback of correct orientation and tolerance during the construction on site (Fig. 5).

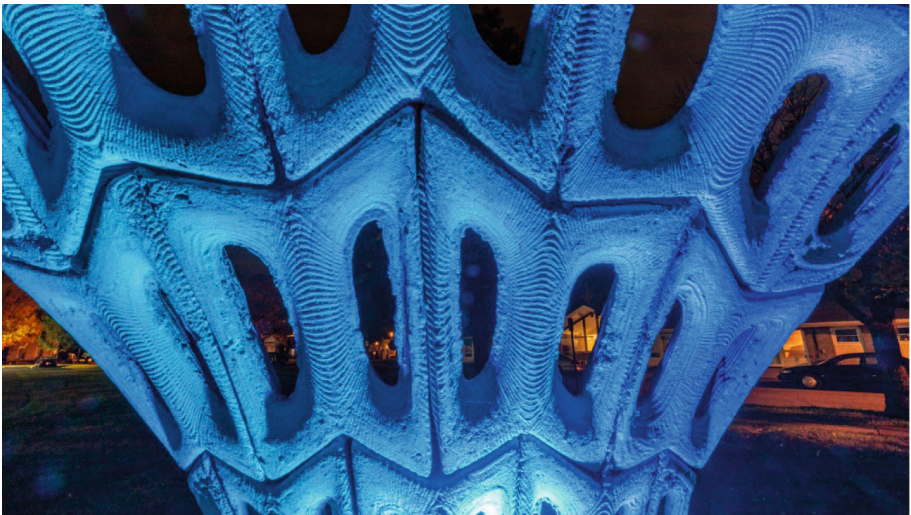


Fig. 5. Bespoke panel interlocking geometry for pre-cast compression structures.

Through the design of the extrusion print path within the sand mold geometry, it was imperative that the mortar material be consistent in creating solid concrete geometries without cold joints and exhibit the structural strength of cast concrete. Developed for the project was a growth algorithmic print path that resulted in an interlacing of the 3D mortar, essentially weaving the viscous material while also integrating the precision associated with this technique of material deposition. The tolerance of the nozzle from the sand wall edges created the space needed for over extrusion of the material to create the casted edges. The material in the undercuts associated with edge conditions was placed under pressure by surrounding mortar material through the toolpath sequencing ensuring a clean cast. Openings within the panels were generated through the printing technique without the necessity of additional material as part of the green sand mold. By interlacing the mortar, the cold joint associated with concrete 3D printing was eliminated and full rebar emersion and integration was achieved per panel. The average extrusion time per panel for the project was 20–40 min, depending on the length of robotic toolpath. Periodic purging maintained that fresh 3D mortar was moving through pumps, hoses, and extruder reducing the risk of clogging or equipment failure. A pause in the tool path was designed to allow the placement of the rebar during the extrusion process.

4 3D Printed Mortar Properties

The material used for this project is 2nd generation of LATICRETE ® 3D Printing Mortar, a commercially available 3D printable mortar produced by LATICRETE International, Inc. This mortar is developed from the prototype 3D mortar produced by LATICRETE’s team [14] and is specifically designed for 3D construction printing (3DCP) application. All the tested specimens were produced by mixing LATICRETE ® 3D Printing Mortar with water at 21:4 weight-ratio. The fresh properties of the mortar is presented in Table 1 below. The wet density of the freshly mixed 3D mortar is measured by filling and weighing a 100 ml density cup with the mortar. The viscosity of the mortar was measured by using Brookfield viscometer with spindle #14 at 10 rpm with a reading taken every 15 s for two minutes. The flow and initial set time of the fresh mixture were measured following the ASTM C1437 [15] and ASTM C266 [16], respectively.

Table 1. The fresh properties of LATICRETE ® 3D Printing Mortar

	LATICRETE ® 3D Printing Mortar
Wet density, gram/cubic-centimeter	1.89
Flow, % (ASTM C1437 [2])	59
Viscosity, Pa · s	31.250
Initial set time, minute (ASTM C266 [3])	110

The compressive and tensile strengths of the hardened mortars were assessed by following test ASTM C109 [17] and ASTM C307 [18], respectively. The test results are shown from separately cast specimens in Fig. 1.

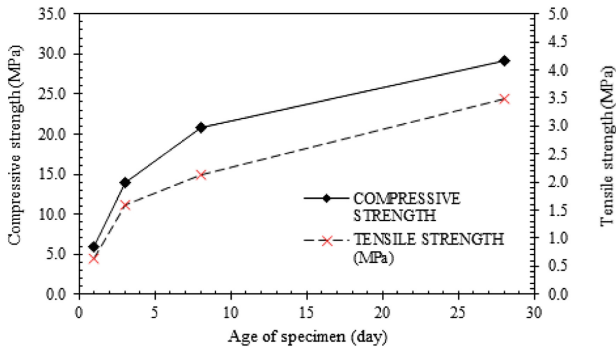


Fig. 6. The compressive and tensile strengths of LATICRETE® 3D Printing Mortar.

Both the compressive and tensile strength of the mortar increases as the hydration progresses. The compressive strength of the mortar rises from 5.9 MPa at 1 day to 29.2 MPa at 28 days. Similarly, the tensile strength increases from 0.6 MPa at 1 day to 3.5 MPa at 28 days (Fig. 6).

5 Future Investigations

Utilizing this method for concrete construction has direct implications for both on site construction and pre-cast fabrication. The flexibility of fabrication, speed of mass customization, and the precision of casting allows this technique to be implemented within existing pre-cast industrial facilities. With the addition of a robotic fabrication platform, mass customization could be integrated within existing established plants expanding upon their geometric capabilities. The infrastructure for moving fabricated components, storing, mixing of concrete, pumping equipment, and the knowledge of plant workers specialized working with mortar, could allow for an easy transition to the industrial scale. Developed within the research lab under university constraints, the ability to scale within the controlled environment of the pre-cast industry would allow for the more efficient used of material in relation to structural loads, detailed connection geometry to inform construction on site, and the reduction of cost associated with fabricating new molds in relation to the changing demands of the concrete industry.

Rapid on-site construction is also possible with the development of a mobile robotic platform. On site robotics is becoming increasingly prevalent where construction workers and industrial robots work in tandem to construct complicated precise geometries. Having the ability to bring the fabrication platform to the construction site that has the precision and speed of a pre-cast concrete facility; could be utilized in large infrastructural projects, projects with remote locations, or to reduce infrastructural costs associated with onsite cast in place applications. Once the robotic platform is delivered, green sand tooling allows for the recycling of bespoke molds and continued fabrication

without additional material. The use of 2nd generation of LATICRETE ® 3D Printing Mortar allows for onsite printing without mixing and measuring of dry materials, streamlining onsite fabrication. Components after curing can then be craned into place onsite, eliminating the transportation logistics associated with traditional precast construction.

6 Conclusion

The process of additive manufacturing has continued to rapidly evolve over the past decade with various processes impacting the industry. Through the continued development into additive manufacturing material science and post-production fabrication techniques, the relationship between 3D printing and support materials are evolving. Projects that have looked at support material in the development of printing technology such as *Sub-Additive Manufacturing*, *Informed Ceramics: Multi axis Clay 3D Printing Freeform Molds* [19], and *Multimode Robotic Materialization* [20] shift manufacturing bespoke components from planar constructs to complex double curvature geometries. Through the use of computational structural analysis in the design of architectural and infrastructural geometries, the material efficiency of precise material robotic deposition, combined with the ability for rapid bespoke forms with cast edge conditions, the research developed in *Print-Cast Concrete* has the ability to be implemented seamlessly in existing pre-cast fabrication plants. The research also has the ambition of bringing mobile pre-cast concrete fabrication to complex on site construction situations continuing the advancement of pre-cast concrete techniques. The robotic platforms and infrastructural cost associated with the method are reduced with the ability to recycle mold tooling materials and minimize project costs through the efficient fabrication of concrete geometry at the scale of mass customization.

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3D Printing of a Cement-Based Mortar in a Complex Fluid Suspension: Analytical Modeling and Experimental Tests

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Abstract. New techniques of 3D printing bring innovations to the construction industry. However, printing cantilevered elements or complex geometries which initially need some temporary support or lost formwork to ensure their mechanical stability is still challenging with 3D extrusion printing. A possible way is to print them directly in a yield stress fluid which could ensure their stability. In this study, a cantilevered cementitious material was printed in a Carbopol gel where the stability of the element and its geometry were thoroughly investigated. The rheological properties of the Carbopol gel and mortar were tailored to sustain the gravity effect of the cantilevered structure and an analytical model has been developed to propose an optimization method of the rheological properties of both the yield stress fluid and the mortar. In order to validate the model, experimental investigations have been carried out by images tracking. The developed model is reliable with the experimental data considered of the densities, the yield stress of both materials and the geometry of the printed shape. The prediction of failure by bending is possible, implying that the model could help making better designs of complex cement-based elements and optimizing their temporary support with elasto-plastic fluids.

Keywords: 3D printing · Yield stress fluid · Cementitious material · Rheology

1 Introduction

Manufacturing industries within automotive or aeronautic fields make large use of 3D printing because of its various advantages. This method was initially defined as the production process that makes physical objects layer-by-layer [1]. This technique evolves in the construction industry with the use of new devices such as gantry printer or 6-axis robotic arm [2, 3]. Those devices allow a free and controlled displacement of an extrusion system, following complex and well-defined trajectories in a three-dimensional limited space and allow more freedom in comparison to layer by layer printing.

Among the innovative printing developed nowadays, bio-printing of human organs can be noted, where complete heart, nose or other organs are printed into a liquid suspension [4, 5]. This process makes it possible to print free shapes and challenges the traditional additive manufacturing techniques [6, 7].

In the construction sector, cement-based mortars are increasingly considered for 3D printing [8]. These materials behave roughly as visco-plastic Bingham materials. They flow only when submitted to stresses higher than a critical threshold value called yield stress [9]. Several studies show that structural stability [10], buckling [11] and rheological requirements [9] could help to predict the stability of the printed elements.

Depending on shape or architecture of the printed element, several scientific and technical challenges remain unanswered in order to produce cantilevered element in a 3D concrete printing process. The usual solution with extrusion technique is to print the structure with the help of temporary or a lost formwork [3, 9]. Another solution is to print structures with selective method [12, 13]. However, 3D printing of cementitious material into a complex fluid could help to support the weight of the printed cementitious material and to preserve its geometry until hardening [14, 15]. The printed element is subsequently extracted from the tank and the gel can then be recycled.

To our knowledge, there is a lack of studies highlighting the interest of this approach for future applications in construction industry. Thus, the objective of this work is to propose an analytical approach, which can help to define a stability criterion of the printed element. With this aim, the Carbopol gel suspension and a 3D-printed cement-based mortar have been retained. An assembly of a column and beam was printed in this study (such as inverted “L” letter). Finally, the predicted failure is comparable with the observed failure.

2 Materials and Protocols

2.1 Tested Materials and Mixing Procedure

Carbopol

Carbopol gel is a yield stress fluid often used for rheological laws validation [16, 17]. The used raw material is the Ultrez 20 Carbopol powder, supplied by Lubrizol. This material is a high cross-linked polyacrylic acid polymer synthesized in benzene [18]. The rheological properties of such gels (elasticity and yield stress) are affected by the mixing procedure and its composition. In order to obtain the gelation, it is necessary to neutralize the acid functions grafted onto the polymer chain using a base solution [19]. Therefore, a sodium hydroxide base solution (NaOH) is prepared at 18% mass concentration and added to Carbopol acid solution within a 2.3 base/acid ratio [20]. The produced gel remains stable, thick and homogeneous. The mix-design of the gels at different Carbopol powder mass concentration is shown in Table 1.

Table 1. Carbopol gels composition

Carbopol powder amount (%)	0.2	0.5
Distilled water (g)	30 000	30 000
Carbopol powder (g)	60	150
NaOH 18% solution (g)	138	345
Density ρ_c (kg · m ⁻³)	1001,6	1003,9

These compounds were prepared by slowly adding the powder to distilled water. The mixture is stirred slowly with a variable speed mixer to disperse the powder and reduce the air bubbles formation within the suspension. The dispersion is then neutralized with the NaOH solution. After this step, the suspension is divided and distilled water is added to obtain samples with different range of yield stress as shown in [17]. The density of the Carbopol gel suspensions is ranged between $1001\text{--}1004 \text{ kg} \cdot \text{m}^{-3}$. These values are very close to water density due to the low polymer concentration. Each sample is then stored in a container at a controlled room temperature ($\sim 20^\circ\text{C}$) before testing.

Cement Based Mortar

In order to produce an extrudable cement-based material, a formulation has been developed regarding printability. The mix-design contains a viscosity modifier agent, superplasticizer, water, sand and cement.

The viscosity modifier is prepared by dissolving 1.5 g of Cellulose Ether powder (Tylose® MH 10000 KG4) in 40 ml of water using the specifications proposed in [21]. Then, a cement-based mortar is prepared by mechanically mixing cement powder (CEM I 52.5 N from Calcia Gaurain) with standardized sand 0/2 mm (in accordance with EN 196-1 & ISO 679 from SNL). A standard mortar mixer is used for this operation and the room temperature is fixed to 20°C . The sand/cement mass ratio ($S/C = 1$) is selected to ensure an extrudable texture [22]. The water/cement mass ratio ($W/C = 0.36$) is thus retained to obtain an extrudable material which is able to retain its shape under gravity. The amounts of superplasticizer and viscosity agent are chosen in typical range of industrial recommendations (0.1% by weight of cement). In parallel, dry materials are mixed for one minute at very low speed (40 rpm). After that, water, superplasticizer (Tempo 12, Sika) and the prepared viscosity modifier agent are added to the dry mix and mixed at a very low speed (40 rpm) for one additional minute. In the next step, the mortar is mixed for 30 s at low speed (140 rpm). After one minute of rest time, the bottom of the mixer bowl is scraped and the mixture is then mixed at high speed (285 rpm) for one minute. The bulk density of the fresh mortar is $\rho_m = 2188 \text{ kg} \cdot \text{m}^{-3}$.

3D Printer Device

The used 3D printer is the BK3D for Universal Concrete Printer (BK3D-UCP), homemade in the L2MGC lab (Fig. 1a). This device is a 3-axis gantry [3], equipped with an electronic control system which allows free movements of the printer head in any orientation of the three-dimensional limited spaces. The extrusion velocity depends on the nozzle geometry, its roughness and the printed material rheological properties. Taken into account the formulated material, a circular nozzle with a diameter of 18 mm is used. The material flow rate and the travel feed rate are respectively equal to $2.5 \text{ cm}^3 \cdot \text{s}^{-1}$ and $1 \text{ cm} \cdot \text{s}^{-1}$.

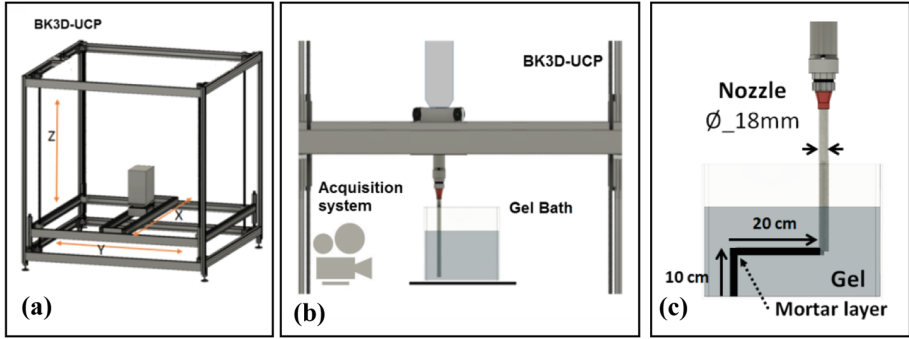


Fig. 1. Schematic representation of the developed 3D printer “BK3D-UCP” (a), printing head into a gel bath equipped with a visualization apparatus (b) and printing parameters (c).

An inverted “L” layer has been chosen as a printed shape to simplify the study and focus on the stability of the horizontal part. As shown in Fig. 1c, the printing starts from the bottom in the gel volume and rises 10 cm to create the vertical part (column). Then the printer moves horizontally to create the 20 cm long beam of the inverted “L”. The viscosity effects can be neglected in the analytical approach as the mass flow rate remains very slow [23].

Rheological Measurement

The rheological measurements were carried out with a MCR102Anton-Paar rheometer equipped with Vane tool geometry for both the Carbopol gels and cement-based mortar. Shear tests have been carried out following the protocol used in [24], which consists of applying a small and constant shear rate until destroying the micro-structure. Due to the thixotropic nature of the cement-based material [25], the tests were done few minutes after mixing [26]. The yield stress τ_0 was calculated by measuring the maximum torque T using the Eq. (1) or from the shear stress τ versus shear strain γ curve ($\tau = f(\gamma)$) [27, 28].

$$\tau = \frac{T}{2\pi hR^2 + n \cdot 2\pi R^3/3} \quad (1)$$

Where h and R are respectively the height and radius of the Vane geometry, n is a dimensionless coefficient which takes into account the base effect of the Vane tool only, in order to calculate the shear stress [27]. The Young modulus is deduced from the shear elastic modulus using the Eq. (2) and $G = \frac{\tau}{\gamma_c}$ is deduced from the shear stress versus shear strain curve considering the linear part, with γ_c the critical shear strain at flow on set (Fig. 3).

$$E = 2G(1 + \nu) \quad (2)$$

Analytical Approach

The mechanical stability of the inverted “L” printed in the gel is presented in this section and the main data of the studied geometry are reported in Fig. 1c. The vertical and horizontal parts are assumed to be well represented by a cylindrical geometry and the slenderness ratio of that geometry (e.g. (beam cross section)^{1/2} << beam length) is well adapted to insure the use of beams theory in this analytical approach. The mechanical stability close to a static approach considers the gravity effect, the mechanical action in the bend of the geometry, the mechanical rigidity induced by the gel and the drag force between the gel and the cement-based material [4]. In the present study, the rheological behavior of the gel and the mortar is assumed to be perfectly elasto-plastic. For a critical strain induced in the gel, the limit shear stress is reached at the limit of elasticity.

The drag force F_D exerted upon the beam is expressed by Eq. (3). In this equation, τ_0 represents the yield stress of the gel suspension and $A = 2rL$ represents the projected area of the beam along a horizontal plane, where r and L are respectively the geometry radius and length. This force tends to avoid the printed layer movement in the Carbopol gel. Equation (3) is only meaningful when used at infinitely low velocities where the inertia and viscous effects are negligible in comparison to the yield stress effects [23]. For the static representation of the stress exerted on the horizontal part of the deposited layer, the forces balance exerted on the horizontal layer is summarized in the Fig. 2.

$$F_D = \tau_{0,gel} \cdot A = \tau_{0,gel} \cdot 2rx \quad (3)$$

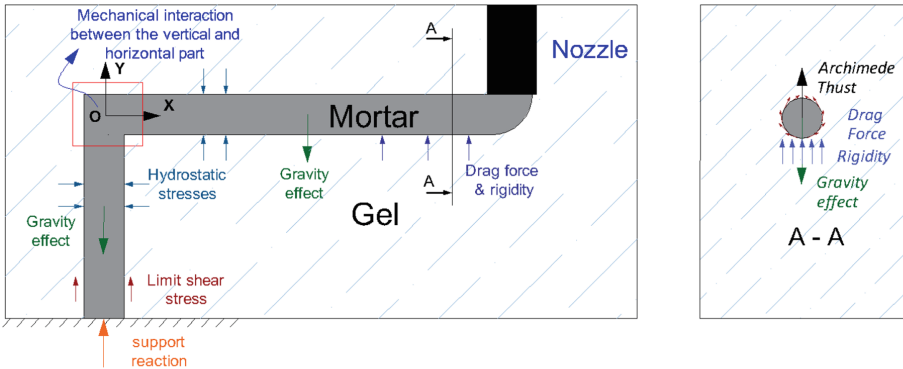


Fig. 2. Schematic illustration of the forces balance exerted on finite horizontal part of the layer.

Considering the supporting capacity of the Carbopol gel, the forces balance of the structure can be written using the equilibrium Eq. (4).

$$\begin{aligned} \sum \vec{R} &= \vec{F}_G + \vec{F}_A + \vec{F}_D + \vec{F}_R + \vec{R}_{V/o} + \vec{R}_N \\ &= ((\rho_c - \rho_m)g\pi r^2 x + 2\tau_{0,gel}rx + F_R + R_{V/o} + R_N)\vec{y} \end{aligned} \quad (4)$$

Where $\overrightarrow{F_G}$, $\overrightarrow{F_A}$, $\overrightarrow{F_D}$, $\overrightarrow{F_R}$, $\overrightarrow{R_{V/o}}$ and $\overrightarrow{R_N}$ are respectively the gravity force, the Archimedes effect, the Carbopol gel drag force, the rigidity effect uniformly distributed along the length of the beam, the bend reaction between the vertical part and the horizontal part of the cantilever and the reaction of the outputted mortar in connection with the nozzle. Within this study, the gel rigidity effect is assumed to be well represented by Eq. (5), considering only the gel situated under the horizontal part which exerts this effect that depends on the supporting fluid properties and the dimensions of the extruded layer.

$$F_R = 2rE_c\epsilon_{crit}x \quad (5)$$

Where E_c is the Young's modulus of the Carbopol and ϵ_{crit} is the beam's critical strain.

Then, based on Eq. (4) and moment equation, $\overrightarrow{R_{V/o}}$ and $\overrightarrow{R_N}$ can be estimated. However, once the extruded layer evolves in the gel, the internal stresses of cement-based mortar can thus contribute to resist the spontaneous break down of the printed shape. The bending moment creates an internal normal stress σ_{mortar} in the mortar, which is expressed in Eq. (6). The maximum normal stress can be thus deduced from the maximum of the bending moment.

$$\sigma_{max,mortar} = \frac{-M_{f,max}y}{I} = -\frac{x^2y}{8I}((\rho_m - \rho_c)g\pi r^2 - \tau_{0,gel}2r - 2rE_c\epsilon_{crit}) \quad (6)$$

Where y is equal to the radius of the cross section of the beam corresponding to the nozzle radius, and I is the inertia moment of the circular section. The internal normal stress σ can be therefore compared to the admissible intrinsic normal stress of the cement-based mortar $\sigma_{N,adm,mortar} = \sqrt{3} \cdot \tau_{0,mortar}$ which can be expressed by Eq. (7) taken into account the Von Mises yield criterion [28–30].

$$\left| -\frac{x^2y}{8I}((\rho_m - \rho_c)g\pi r^2 - \tau_{0,gel}2r - 2rE_c\epsilon_{crit}) \right| < \sqrt{3} \cdot \tau_{0,mortar} \quad (7)$$

Where, $\tau_{0,mortar}$ is the yield stress of mortar, measured by a Vane rheometry technique. Consequently, the bending and the failure position of the beam can be predicted by comparing those stresses. In this case of stability evaluation, elasticity (or rigidity) will become systematically the dominant rheological requirement at the end of the printing process [9]. However, the results of the model can be retained as a stability criterion only if the sum of forces remains positive.

3 Results and Discussion

3.1 Rheological Measurements

The results presented in the Fig. 3 sum-up the rheological measurements. The yield stress of the Carbopol gel increases when increasing the Carbopol amount. The yield stress is computed from the maximum measured torque. In addition to the yield stress

analysis, gels and mortar exhibit a roughly elastic behavior at low shear strain in the beginning before the critical shear strain. The shear elastic moduli values are presented in Table 2. These results allowed the identification of the Young's modulus.

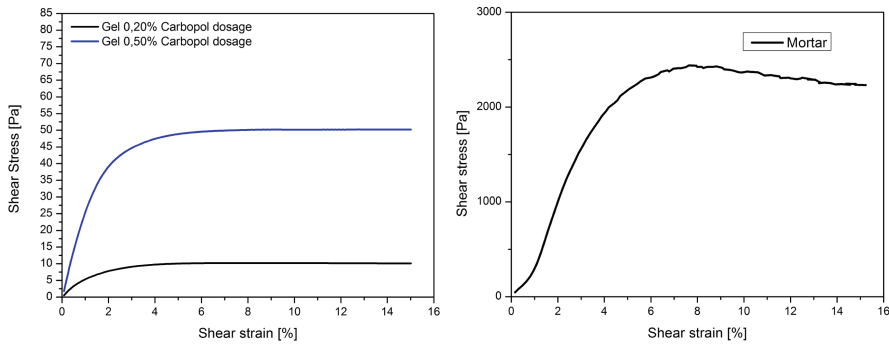


Fig. 3. Evolution of the shear stress versus the shear strain for both gels (0,2% and 0,5% Carbopol dosages) and the printed mortar.

Table 2. Rheological properties of materials

Material	Yield stress [Pa]	Shear elastic modulus [Pa]	Elastic modulus [Pa]	Critical strain [%]
Carbopol gel 0,2%	10,2	358,1	1074,2	2,5
Carbopol gel 0,5%	50,3	2196,8	6590,5	2,2
Cement-based mortar	2437,6	53386,1	138803.9	4,0

3.2 Visualization of the Process

At low a Carbopol amount (i.e. 0.2%, Fig. 4a), the vertical part of the printed structure can be well manufactured. The vertical velocity of the printer is also well adapted because of the apparent constant diameter of the column. However, for fixed altitude as soon as the horizontal movement of the printer started, a rotation of the vertical column was observed. Then, visualizations show a quick collapsing of the printed structure. Such a result is a good illustration of non-adapted rheological properties of the gel.

A higher Carbopol amount (i.e. 0.5%, Fig. 4b) showed that it is also possible to manufacture the vertical part of the reversed “L” without adjustment of the printer parameters (cement flow rate, head printer velocity). Nevertheless, a gentle diameter evolution is observed between the basis and the top. Then, when the horizontal movement started, the rheological properties of the gel were sufficient to prevent the rotation of the vertical column. Additionally, the overhang was largely supported even if a minor deformation of the horizontal beam was noted.

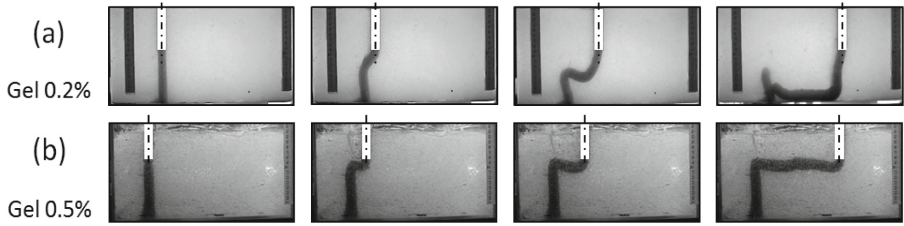


Fig. 4. Photography of printing process into both gels (0.2% and 0.5% Carbopol dosage).

3.3 Validation of the Analytical Model

The analytical model predicts stability from Eq. (7). Specifically, the absolute value of the stress resulting from the maximum bending moment should be lower than the admissible normal stress (related to the yield stress in Eq. (7)).

The failure of the printed shape in the first gel suspension (Fig. 5a) is over estimated (because the calculated length of failure is slightly greater than the observed one) but it refers to the real case during the printing process shown in Fig. 4a. Under the same conditions, but with the other gel suspension (Fig. 5b), the balance-stress values remain between the limits of the mortar's internal stress. This explains the stability of the shape (see Fig. 4b), but also suggests that 20 cm is the maximum print length within such these conditions.

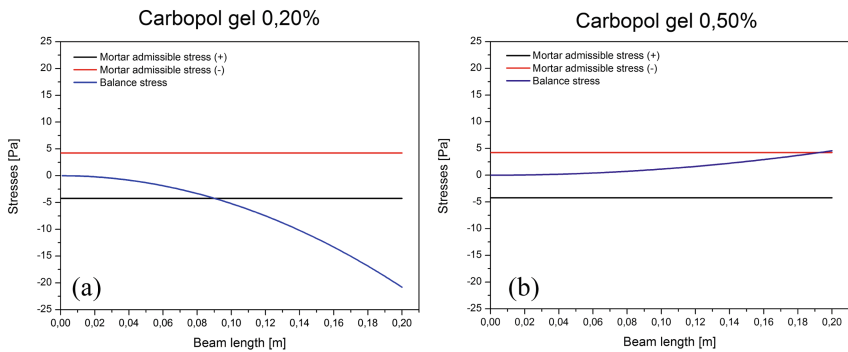


Fig. 5. Balance stresses applied on the beam versus the beam length printed into gels with (a) 0.2% and (b) 0.5% Carbopol amounts.

4 Conclusion

This study allowed modeling of the exerted stress on a cantilevered shape of cementitious mortar extruded into suspensions of Carbopol gel to improve its stability. Responses given both by images analyses and the analytical model are in good accordance. Possible stability of the printed element has been highlighted. The model

can help to define a criterion that relates to the physical and rheological properties of both fluids (cement-based mortar and gel) to satisfy the stability of the printed shape at early age. The prediction of the failure by bending will become possible using the proposed model which could help for the mix-design of the mortar and the temporary support made by yield stress fluids. In the cases of a low Carbopol dosage gels (0.2%) the gel cannot support the shape where a weak zone and failures can be observed as large deformations. However, when printing into a 0.5% Carbopol amount gel, the shape remains stable, at least up to the tested length of 20 cm. Improvements to the models must be made in particular to quantify the evolution of the rheological properties of the gel, which is affected by the chemical reaction due to the pH difference at the gel-mortar interface. This work is, however, an encouraging first step in modeling 3D printing into yield stress fluid. An important application of the model will probably be to determine the types of shapes that may be printed, considering the realistic properties of the supporting gel.

Acknowledgement. The results presented are part of the “Cod-Imp4D” project funded by the foundation of the University of Cergy-Pontoise (2018–2019) and of the current research work entitled “3D printing of materials dedicated to construction”, funded by a grant from CY Paris University Science and Engineering doctoral school (EDSI). The authors thank them for the financial support.

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Experimental Study on 3D Printing of Concrete with Overhangs

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Abstract. The construction industry has been receiving in the recent past years the 3D printing technology as an emerging technology. Several researchers and companies have been reporting a number of case studies that show the possibilities of this technology regarding the dimensions, shape, building time, finishing and the material characteristics. It is commonly accepted that one of the big advantages of 3D printing is its possibility regarding the shape of the printed object since it can be easily changed each time a new piece is printed. This possibility raises some challenges regarding the printing limits, that are needed to the project design, such as to create overhangs. In this sense, a work was carried out to evaluate and optimize concrete printing mixtures and assess the 3D concrete printing of elements with overhangs. This paper presents the work carried out, showing the optimization of mixture composition for the binder/aggregate ratio, cement/fly ash ratio, and amount of superplasticizer and hardening accelerator, and evaluating their printing performance and mechanical properties. Printing of overhangs was possible for angles with the vertical direction till 17.5°.

Keywords: 3D printing · Concrete · Design · Overhangs

1 Introduction

Concrete 3D printing is a game changer in the building industry. It gives the ability to optimize the way constructions are made while being much more sustainable. With 3D printing, the use of complex shapes becomes easier, and this technology can be used for an architectural standpoint as well as for more technical applications, as the example given by the Dezeen x MINI Living, made from soil and agricultural waste by Wasp [1]. This, allied with numerical simulation, becomes possible to use exactly the material required for the construction, avoiding waste and reducing production costs. With this new technology, the production of overhangs or topologically optimized walls becomes viable as well as organic shapes [2].

This is a great breakthrough not only in building industry but also in terms of specialized materials, since this new building process will require custom materials for the different uses and multi material applications.

1.1 Design in 3D Concrete Printing for the Construction Industry

A growing number of researchers and enterprises developed different ways to produce 3D concrete printing (3DCP) [3]. Different design approaches and geometries have been produced by different entities in order to surpass the limitations of cementitious materials. These materials distinguish themselves from other materials used in additive manufacturing because of the setting times of the cement which can vary widely with the mixture used, printing size and parameters [3].

One of the first examples of this technology is the Wonder Bench by the Loughborough University [4]. It consists of 128 layers directly stacked on top of one another, resulting on a relatively easy design. Another example is the interior of a hotel suite printed by Andrey Rudenko using sand and volcanic ash from local sources, and included a twisted pillar design that not only is appealing to the eye but also shows the possibilities of shifted layers in 3DCP [5]. Winsun did the first 3D printed office buildings in Dubai in a fibre glass reinforced concrete. The buildings have a modern look with round surfaces [6]. Another good example of the design possibilities in 3DCP is the printed wall by Gosselin et al. with printed slopes (overhangs) without external supports, using an ultra-high performance concrete [7].

Overhanged layers allow a wide array of topologically driven organic shapes. This allied to computer simulation software reduces drastically the quantities of wasted material as well as provide some sort of aesthetic element to the building itself. Despite overhangs are quite difficult in extrusion-based 3DCP technique, because it takes time for the bottom layers to set, there is a need for development to explore the limits of the technique.

1.2 Mixtures Optimization for Concrete 3D Printing

In the process of additive construction with concrete materials, some challenges to its full development are found. In principle, the concrete 3D printing is self compacted, having its critical point in the fresh properties, which can be described by the pumpability, extrudability and buildability. This is mainly influenced by properties of the mortars such as the open time, layer cycle-time, deformation under self-weight and rheology [8], which depends on the mixture's composition. The concrete can have different compositions that rely heavily on the performance to be achieved. The properties of the fresh and hardened properties have been investigated [9–11]. To enhance their properties, admixtures, supplementary cementitious materials and fibres have been used.

Superplasticizers are widely used admixtures to improve workability, but can also be used to maintain the workability reducing the water content [12], despite they can slow the hardening process [13]. The hardening accelerators, such as calcium chloride, increase the early strength of the concrete, given the ability to speed up hardening times of the concrete, enabling faster execution of the works [14, 15]. This increase in the

hardening rate has an important role in the additive process, so that the lower layer has enough yield stress and stiffness to the next overlaid layer.

The fly ash is a pozzolanic material that has benefits on the improvement of the fresh mixture, increasing cohesion, viscosity and plasticity, and reducing the bleeding and segregation [16]. Fibres are incorporated into cementitious materials in order to enhance their ductility, dynamic properties, poor resistance to shrinkage cracking and after cracking resistance [17–21].

Mixture optimization was done by Rubio et al. [22] that applied a binder/aggregate ratio of 1:2 and 1:3. The addition of fibres in a proportion of 0.2 to 0.6% increased their yield stress, and their cohesion become more stable so as to not collapse with the above layer. The addition of fly ash and silica fume in the proportions of 24% and 8% respectively, gave an increase in the yield stress, cohesion, homogeneity and stability to print because the reduced segregation and slump. Le et al. [13] used five mixture compositions to identify ideal proportions for printing on concrete. The proportion of aggregate/binder having better result was 60% and 40% respectively, and the binders included 20% of fly ash and 10% of silica fume. The superplasticizer was between 0.5% to 1% of the binder weight, and polypropylene fibres dosage was of 1.2 kg/m³.

As described above, many examples with challenging shapes were done. However, the limitations of 3D printing with concrete remains to be fully studied, namely for printing overhangs. In this sense, a work was done regarding the optimization of the mixtures composition and its printability regarding the construction with overhangs in 3DCP.

2 Mixtures and Printing Processes

2.1 Printing System

The equipment used for 3D printing tests consists of a robotic arm Yaskawa Montoman HP20F model with a payload of 20 kg, and having six axes, namely: sweep, lower arm, and upper arm, rotate, bend and twist as shown in the Fig. 1.

The robotic arm controller is a FS100, which is programmed to make the arm draw the desired path. A printing head for cementitious materials was coupled to the wrist part of the robotic arm. A storage tank of 5 L of concrete was assembled to the robotic arm for pumping concrete through air pressure. The parts of the storage tank are an aluminium cylinder, piston, closing upper and lower heads, aluminium brackets and components to facilitate and secure the locking system. The system operates by an electric motor so that the concrete was continuously printed through the screw extruder.

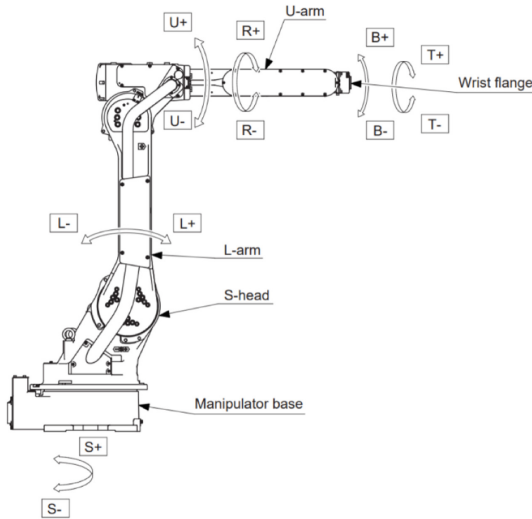


Fig. 1. Printing equipment

2.2 Concrete Mixtures – Printing and Properties

Mixtures

In this study, 17 different concrete compositions were tested, so as to evaluate the printability and the possibility of printing overhangs.

The cement used was of the type CEM II A/L 42.5 R. Fly ash was also used to improve the fresh mixture properties, having loss on ignition lower than 7%, fineness of 16%, a total calcium oxide content lower than 10% and particle density of 2300 kg/m³, according to the manufacturer. Two types of rock aggregates were used: granite and limestone. Both were provided by the company Lena Agregados as low commercial market value aggregates or become waste by extractive industries. For the purpose of tests, aggregates had a maximum size of 2 mm to be suitable for the printing equipment. The admixture superplasticizer Viscocrete from Sika was used and also the hardening accelerator MasterX-Seed 130. Polypropylene fibres were also used from REPSOL-química, S.A., having an average diameter of 31 µm and an average length of 12.9 mm.

Printing tests

The experimental work comprised two phases. The first phase had the objective of optimization of the mixture in order to find a homogeneous concrete with good buildability and visual appearance by printing the square shown in Fig. 2a. Five mixtures were tested, as shown in Table 1, with the objective of obtaining the mixture that gives best results, depending on the type of rock, aggregate size, binder/aggregate ratio and the amount of superplasticizer. The water/cement ratio was used in order to obtain a concrete plasticity in printable region as defined by Tay et al. [23]. For the printing parameters a nozzle travel speed of 40 mm/s was used, for a target layer width of 20 mm and the layer height was of 8 mm.

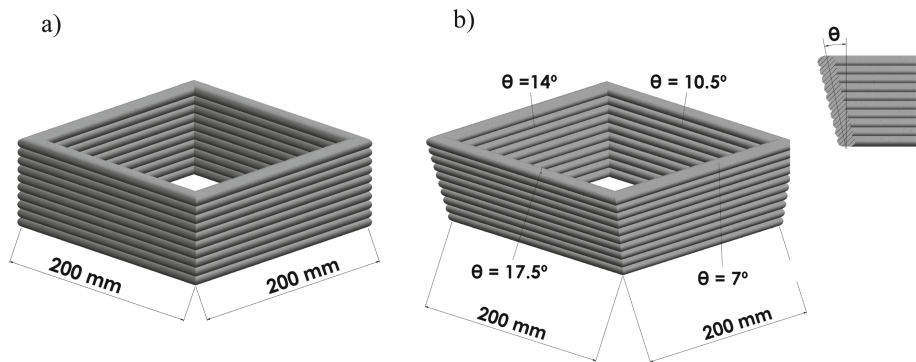


Fig. 2. Drawings of the specimens printed: a) mixture optimization experiments (with no overhang), b) printing of overhangs experiments

Table 1. Mixtures optimization.

Mixture	S1	S2	S3	S4	S5
Rock type	Limestone	Granite	Limestone	Limestone	Granite
Maximum diameter	1 mm	2 mm	1 mm	1 mm	1 mm
Binder/aggregate ratio* (%)	40/60	40/60	50/50	60/40	50/50
Cement/fly ash ratio* (%)	75/25	75/25	75/25	75/25	75/25
Water/cement ratio* (%)	41	45	35	30	39
Superplasticizer (%)	0.5	0.5	1	1	1

* – refers to mass ratio

The second tests phase had the objective of studying the printing of overhangs, by giving a horizontal offset in the successive printed layers. The horizontal offset was done to give four different slopes (7°, 10.5°, 14° and 17.5°) for each square side (Fig. 2b). The above mentioned printing parameters were used. For this second phase, limestone type rock was selected, having maximum size of 1 mm. A binder/aggregate ratio of 50/50 was used, given the better results obtained in the first phase for this ratio. This study on printing overhangs included also the optimization of the mixture composition for: i) water/cement ratio, amount of superplasticizer and hardening accelerator (mixtures D1 to D5), ii) cement/fly ash ratio (mixtures D6 to D9) and iii) the use of fibres (mixtures D10 to D12) as shown in Table 2.

The results obtained on the printing tests were evaluated visually, by observation of the quality of the surface and possible splitting, tearing, deformation and failure on the fresh specimens. The overhanging limits were established for specimens where, although a possible low surface quality, printing was successful with no apparent anomalies.

Table 2. Mixtures tested in the printing of overhangs.

Mixture	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
Cement/fly ash ratio* (%)	75/25	75/25	75/25	75/25	75/25	80/20	70/30	65/35	60/40	70/30	70/30	70/30
Water/cement ratio* (%)	35	35	36	40	34	36	36	36	36	36	37	38
Superplasticizer (%)	1	1	1	1	1.5	1	1	1	1	1	1	1
Hardening accelerator (%)	0.5	–	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fibres (%)	–	–	–	–	–	–	–	–	–	0.6	0.4	0.5

* – refers to mass ratio

Flexural, compressive, consistence and workable life tests

The evaluation done on the printing tests were compared with the fresh and hardened properties of the concrete. For this purpose, mixtures were made with a mechanical mixer according to the recommendations of the standard EN 196-1 [24]. Fresh properties measured were the consistence and the workable life as calibrating parameters for good extrudability and printability. The consistence of the mixtures was measured in accordance with the standard EN 1015-3 [25], and the workable life according to the standard EN 1015-9 [26].

As an indication of the performance for the hardened material properties, the compressive and flexural strength were tested. Each mixture was casted on three moulds with $4 \times 4 \times 16$ cm to perform the mechanical strength tests. The flexural strength tests were performed after 28 days of the specimen preparation. For each mixture three specimens were tested over a three point bending test according to the standard EN 196-1 [24]. The flexural stress required to break each specimen was determined by the Eq. (1).

$$R_f = \frac{1.5 F_f \cdot L}{40^3} \quad (1)$$

where:

R_f = Tensile strength in bending (N/mm^2);

F_f = Force required to break the sample (N);

L = distance between supports (100 mm).

The same specimens tested in bending were then used for testing six specimens in compression for each composition, considering a loading area of 4×4 cm. The strength was determined according to Eq. (2).

$$R_c = \frac{F_c}{1600} \quad (2)$$

where:

R_c = Tension strength to compression (N/mm^2);

F_c = Force required to break the specimen (N).

The fresh and hardened properties are shown in the Table 3, which are discussed below together with the printing results.

Table 3. Flexural, compressive, consistence and workable life results

Mixture	Flexural strength (MPa)	Compressive strength (MPa)	Workable life (min.)	Consistency (mm)
S1	8.47	41.58	30	140
D1	8.46	67.92	15	175
D7	9.20	67.82	30	170
D8	9.11	66.18	30	168
D9	8.28	52.32	15	168
D10	8.54	55.22	15	160

3 Printing Results and Discussion

3.1 Mixtures Optimization

The composition of mixture S1 was based on Lim et al. [11] studies containing a binder/aggregate ratio of 40/60%. The extrudability was good, however, it had a high water/cement ratio showing poor buildability. Mixture S2, which contained in its composition granitic rock of size lower than 2 mm, showed segregation in the filaments, causing filament tearing and splitting and eliminated for future testing. In mixture S3, it was decided to increase the amount of binder, in order to make a 50/50% ratio with limestone aggregate of size lower than 1 mm, and the content of superplasticizer was increased to 1%. The increase in the total amount of binder and superplasticizer has proven to be satisfactory for printing, giving better visual appearance (Fig. 3). Further increase on the amount of binders was tested on the S4 mixture to 60/40% binder/aggregate ratio, however, the mixture in its extrusion process was more difficult, with less workability, resulting in small cracks along the filament.

The good performance of limestone powder smaller than 1 mm led to use of granite rock aggregate less than 1 mm in mixture S5 test with a ratio binder/aggregate ratio of 50/50%. An increased water consumption was necessary on this mixture, which resulted in bleeding, causing not good printing results.



Fig. 3. Mixture S3 printing result

3.2 Printing of Overhangs

Since the best results from the mixture optimization (first test series) were obtained for the mixture S3, it served as a reference for the printing of overhangs.

Influence of water/cement ratio, superplasticizer and hardening accelerator

For mixture D1, the same composition of mixture S3 was used, adding a hardening accelerator with the proportion of 0.5% of the binder. However, the addition of the hardening accelerator was not suitable, showing some cracking. On the other hand, the mixture D2, which has the same composition of the mixture S3, showed to be more fluid than desired, giving very wide filaments, not achieving the proposed overhang. The increase on the water/cement ratio on the mixture D3 showed better results than for mixture D1. However, the further increase on the water content tried on mixture D4 showed to be excessive as the material fell down after 8 printed layers. The increase of superplasticizer on mixture D5 did not showed to be good as the mixture was too much fluid.

The influence of the fly ash content

Taking the mixture D3 as the one with better results, it was decided to evaluate the fly ash content on the printing results of the mixtures D6 to D9. Better results were obtained using an increase on the fly ash content of 5% on the mixture D7 (Fig. 4), improving its fresh state, increasing cohesion and viscosity, and reducing the bleeding and segregation, as reported by Dal Molin [21]. Lower fly ash content used on mixture D6 resulted in filament cracking. On the other hand, the higher fly ash content used on mixtures D8 and D9 improved the extrudability but gave poor buildability, resulting in failure.

Influence of fibres

Given that good results were obtained with mixture D7, it was used as a reference for the evaluation on the fibre content. Percentages of 0.4%, 0.5% and 0.6% of fibre content were tested on mixtures D10–D12. The printing process showed to be more difficult. Adding fibres to the mixture showed to significantly limit the flow of the mix and influenced its workability as also concluded by Rubio et al. [22]. However, printing was possible with the fibre content tested. The printed specimens showed rough appearance exhibiting stretch marks over the surface caused by the fibres.



Fig. 4. Printing result of mixtures D7 and D10

Relation between the mixtures properties and the printing results

The lower strength results (Table 3) obtained are related with: i) the lower binder/aggregate ratio on mixture S1, and ii) the higher fly ash content on mixtures D7–D9. In addition, the mixture D10, containing polypropylene fibres in a proportion of 0.6%, showed no improvement over the mixture D7, decreasing the mechanical strength, the workable life and the consistency.

The consistence results are between 140 and 175 mm, which are similar results to Tay et al. [23].

The mixture D7 showed to be the one with better results, showing good printing results and strength. In addition, the 30 min of workable life of mixture D7 are according to the optimum results obtained by Ma et al. [10]. On the other hand, the workable life of mixture D10 was of 15 min which can be a reason for the not so good results obtained with the inclusion of fibres.

Structural stability of the printed specimens with overhangs

Printing was not possible for overhangs with slopes higher than 17.5° since it had no structural stability. To give a possible explanation for these failures, a 3D finite element model of the printed specimens with overhangs was made, composed of 4 node shell quadrilateral finite elements of 10 mm side, as presented in Fig. 5, to model the specimens shape illustrated in Fig. 2b. The numerical modelling was done using Autodesk Robot Structural Analysis Professional, with the objective of evaluating stresses on the printed specimens to get a possible explanation for the observed behaviour on some specimens that failed and also on the specimens printed with overhangs with slopes higher than 17.5° .

The material properties of the fresh concrete were taken as linear elastic. The modulus of elasticity grows as the concrete age increases. In this numerical model a modulus of elasticity was taken equal to 78 kPa corresponding to the lower results obtained by Wolfs et al. [2]. However, in the analysis done, the modulus of elasticity did not have significant impact on the stresses obtained in this model. The Poisson's ratio used was 0.3.

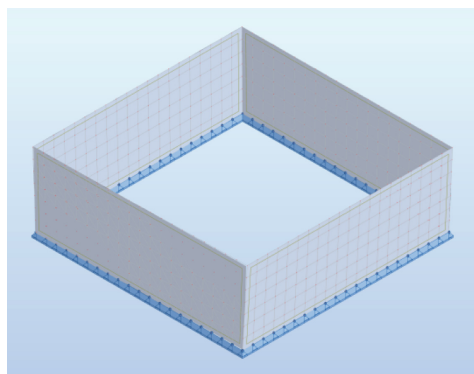


Fig. 5. Finite element model of the specimens

The result for maximum compression stress was 1.88 kPa (Fig. 6a) which is lower than the foreseen strength of the fresh concrete, according to the work of Wolfs et al. [2]. In fact, the visual inspection of the specimen after printing did not show squeezing of the supporting layers, so compressive stresses do not seem to be cause of the failure of some printed specimens. On the other hand, tensile stresses did appear in the upper border of the specimens (Fig. 6b) with a maximum value of 0.18 kPa. Since the fresh concrete should only withstand tensile stresses that are quite nearly zero, this was probably the reason for failure in some specimens. Further work should be done regarding the validation of the model.

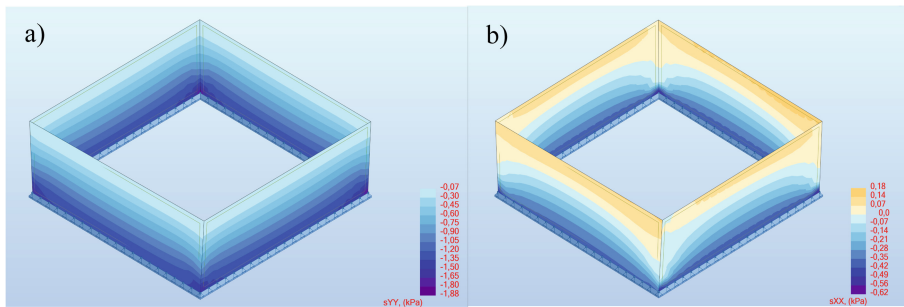


Fig. 6. Finite element model: a) vertical stresses, and b) horizontal stresses

4 Conclusions

A study was carried out on the optimization of 3D printing concrete based materials using low commercial value aggregates and with overhangs. The limestone aggregates gave good results for mechanical strength and printability of the concrete.

For the evaluated mixture design, the best performance for the fresh properties and mechanical strength was obtained for cement/fly ash ratio of 70/30%, using 1% of superplasticizer and 0.5% of hardening accelerator, for consistency of the concrete between 160 and 175 cm, with a workable life of 30 min. The use of superplasticizer played an important role in the mixture rheology, whereas the influence of the hardening accelerator did not seem to be so evident on the mixtures used, probably due to the type of accelerator used.

The 3D printing of specimens with overhangs was possible for angles with the vertical direction of 17.5°. Higher overhanging angle values resulted in failure of the specimens, which seem to be due to tension stresses on the upper border of the specimens.

For a better understanding of the behaviour of fresh printed concrete it is necessary to know the mechanical properties of the material, so as to evaluate possible failure and the printing limits. This should be done in accordance to the concrete mixture used, and its rheological properties. In the finite numerical model analysed, tensile stresses on the upper border of some specimens seem to be responsible for failures occurred during printing.

Acknowledgments. This work is funded by national funds through the FCT - Foundation for Science and Technology, I.P., under the project UID/Multi/04044/2013 and by the National Innovation Agency through the project Add. Additive (add additive manufacturing to Portuguese industry - project number 24533).

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Inspection Methods for 3D Concrete Printing

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Abstract. 3D Concrete Printing (3DCP) is being used for off-site manufacture of many elements found in the built environment, ranging from furniture to bridges. The advantage of these methods is the value added through greater geometrical freedom because a mould is not needed to create the form. In recent years, research has focused on material properties both in the wet and hardened state, while less attention has been paid to verifying printed forms through geometry measurement. Checking conformity is a critical aspect of manufacturing quality control, particularly when assembling many components, or when integrating/interfaces parts into/with existing construction. This paper takes a case study approach to explore applications of digital measurement systems prior to, during, after manufacture using 3DCP and after the assembly of a set of 3DCP parts and discusses the future prospects for such technology as part of geometry quality control for the procurement of 3DCP elements for the built environment.

Keywords: 3D concrete printing · Geometric inspection · Quality control · Additive Manufacturing

1 Introduction

The construction industry has been slower than other industries to adopt automation and digitalization in its manufacturing [1, 2]. This remains the case and the current drive for ‘Industry 4.0’ standards promote the adoption of automation in manufacturing [3, 4]. As a result, many Digital Fabrication processes that form Concrete (DFC) are emerging, with additive methods being the most common [5]. Many demonstrators on

the building scale have been realised, and the science behind the materials continue to be investigated [6–9].

There has been less exploration of the geometric conformity of manufactured parts. Early work that recognised printing resolution issues for 3DCP was presented by Buswell et al. [10], and Buswell et al. [11], with examples of error measurement using photogrammetry in Lim et al. [12]. More recent research has been presented by Xu et al. [13] in real-time varying the bead size to reduce geometric errors, and by Ketel et al. [14] in developing a printability index to link mortar rheology to the geometrical attributes.

Quality inspection is an essential part of quality control [15], based on drawings and specifications detailing the requirements for materials and workmanship, mostly fulfilled via idiographic field testing in casting concrete products [16, 17]. The quality required for reliable assembly of several parts becomes more challenging [18] and in manufacturing, such geometric inspection is often performed on a batch of products using statistical measures [19].

Inspection through digital geometric measurement has become common in construction and manufacturing [20–22], and will play an increasingly significant role, due to the fact that 3D printed components tend to be geometrically more complex and are hence difficult to measure with traditional means. There are different approaches for reality capture that can be applied in 3DCP, which depend on component scales, shape complexity, construction stages, ambient environmental conditions and other technical or economic demands. Classic approaches like using a Total-station are applicable just for simple components. However, 3D laser scanning and photogrammetry-based approach also including structured light-based methods are expressed as the most dominant data capturing approaches [23, 24].

In order for Additive Manufacturing (AM) to find its way into the construction industry in the long term, geometric conformity of 3DCP components to the planned model and specified tolerances of the final products will need to be quantified efficiently using the aforementioned inspection techniques. This applies both to in-situ printed structures on which further building elements, as well as to prefabricated elements that are assembled at the construction site. This paper explores applications of digital geometric inspection methods applied to four stages of the manufacturing and assembly process using 3DCP:

- determining process capability prior to manufacture;
- adaptive fabrication during production;
- evaluating of form for postprocessing; and,
- building documentation after assembly.

2 Background

2.1 Additive Manufacture with Concrete

There are two approaches that utilise the placement of premixed cement-based mortar in a layerwise under digital control. Extrusion-based 3D concrete printing (3DCP) [25]

is similar to the Fused Deposition Modelling (FDM), where fine grain concrete is extruded in filaments and deposited in a layer superposition manner to reach the target geometry [26, 27]. Figure 1a, b and d present examples. Figure 1c presents a material jetting process based on the principles of shotcrete [28] to deposit the material in a similar single nozzle toolpath approach. Both techniques are reported in the case studies presented, although the methods discussed apply to many other processes.

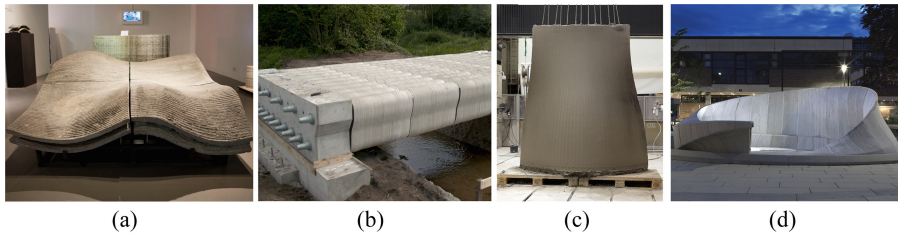


Fig. 1. Typical 3DCP demonstrations: (a) doubly-curved panel (Loughborough University); (b) pedestrian bridge (TU Eindhoven); (c) doubly-curved reinforced wall (TU Braunschweig); (d) COHESION pavilion (University of Innsbruck).

2.2 Geometric Inspection Methods and Tools Applied in 3DCP

Data Acquisition. The data acquisition methods can be affected by parameters like geometric deviations, visualization capabilities, the level of the inspector's experience, and degree of automation [29]. A systematic study and review on this is presented by Kim et al. [24].

3D Laser Scanning. 3D laser scanning and especially Terrestrial Laser Scanning (TLS) has become a common technology to acquire accurate 3D point clouds¹ in many engineering fields. High accuracy, ability to measure long ranges and low dependency on usual atmospheric conditions (lighting in particular) are the main advantages. However, material reflectivity, high cost, level of detail (LOD) dependency on the distance to the object, low portability and operational difficulties in congested areas and possible noise due to moving machinery and personnel in the construction site are limitations [30]. Typical applications of using laser scanned as-built data of components and structures for geometrically dimensional inspection (in comparison to design CAD models) can be found in Akinçi et al. [31], Gordon et al. [32], Bosche [33], and Kim [34].

Photogrammetry. The availability of inexpensive digital cameras has significantly increased the number of photos that are being captured on construction sites on a daily basis [35]. Photogrammetric techniques have an advantage that the sampling is more continuous than laser scanning, although the pixel size is a limiting factor. Challenges

¹ The point cloud is a term used for a set of unordered points, which are spatially sampling an object.

of this approach include: the sensitivity to different lighting conditions, especially regarding severe shadow and low textured surfaces and windows; occlusion: capturing at each standpoint is limited to the closest structural part of the component to the camera; and each component must be visible from multiple (at least two) different points of view and those need to resemble a good image ray intersection geometry. Examples of use in construction include observations using unmanned aerial vehicles (UAV) both outside [36] and inside buildings [37].

Structured Light Scanning. Structured light scanning has been one of the most widely applied optical 3D measurement techniques because of its ease of implementation and fast full-field measurement. Structured light scanners work by projecting a patterned field of light, usually a set of sinusoidal stripes, onto the surface being measured. The set of projected light patterns is then captured using a camera and combined to allow the projected field of light to be unambiguously defined. This allows a process of triangulation to be used to determine the spatial position of imaged pixels to represent points on the imaged surface, creating a point cloud. Short scanning time, high resolution and highly-reduced dependency on material, texture and lighting conditions are the key benefits of this approach. However, this technology only works on relatively small objects located close to the projector.

Coregistration. Often it is desirable to compare the printed object with the digital model and so registration of the measurements with the 3D model must be undertaken often with methods like ICP [38]. Although this approach works in many cases comparing two solid objects, its results could contain bias especially in AM products while ICP tries to minimize the difference between the two entities. Other approaches are to register point clouds and the physical object based on clearly defined targets. Some other researchers used a so-called feature based coregistration for this purpose [34].

3 Case Studies

The following case studies demonstrate inspection at four stages of manufacture and assembly: pre-printing for process and material evaluation, during printing to compensate for plastic deformation, after printing for application of secondary processes, and post assembly for ‘As Built’ records.

3.1 Determining Process Capability: Prior to Printing

The evaluation of process capability in terms of the manufacturing precision is needed to inform the design of the part and as a benchmark for improvement, or system verification checking. Here a ‘standard’ test geometry was manufactured using an extrusion based 3DCP process (Further details in [39]). Positioning of the nozzle was via an ABB industrial robot and material was supplied via a worm pump. Several parts were printed using varying nozzle sizes (8 mm, 12 mm and 16 mm), where the layer height was parametrically linked by a ratio of 0.52, giving respective layer heights of

4.2 mm, 6.3 mm and 8.3 mm. Three parts were manufactured for each diameter using the same hatching pattern and step were taken to minimise the impact of mortar rheology, generating an inspection lot. Each part was then scanned using a DAVID SLS-3 structured light scanner for cost effectiveness and reasonable precision. The scanner performed several scans from different directions to capture the whole part geometry (Fig. 2a). Each scan was then processed (denoising, background removal and ICP registration) using *CloudCompare* [40] to obtain the complete point cloud. This systematic approach can be adapted to isolate influences that might affect the final geometry in a systematic test.

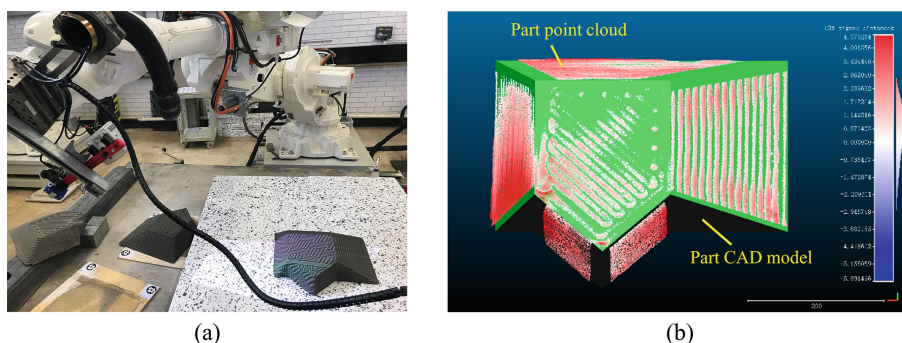


Fig. 2. Structured light-based geometric inspection: (a) data acquisition; (b) flat face profile deviation measurement.

The six flat faces were inspected for flatness and profile errors. For each area, the deviation between each point in the point cloud and the surface of the CAD model was measured (Fig. 2b). The inspected errors allowed the feature tolerances to be evaluated and plotting the data against anticipated effects can help identify unexpected influences. For example, Fig. 3 shows the maximum positive deviation errors as a function of nozzle diameter, for each of the inclined and vertical planes on the part. The well-known ‘staircase effect’ [41] might be expected to dominate and present a linear relationship. The impact of the consistency in the material, even with care, leads to a lack of correlation. The diagrams also demonstrate that the error tends to reduce as the inclination increases because the layer height exacerbates the approximation errors to the flat surface. These insights might then be reasonably applied as constraints in the design of a component, as a benchmark against which improvement strategies can be measured.

3.2 Adaptive Feedback: During Printing

During printing, parameters may be controlled or anticipated a-priori. Others may fluctuate during a printing process, or between printing sessions: environmental conditions or geometric deviations due to cumulative deformations in layers of freshly deposited material for example. Even the exact geometrical properties of the ‘print-bed’ may be unknown. In such cases, the process conditions deviate from expected, which in turn leads to errors or possibly print failure. To avoid this, one approach is using real-time measurement and adaptive feedback.

Wolfs et al. [42] developed a system to perform continuous adjustment of the nozzle height during printing. A 1D Time of Flight (ToF) distance sensor, with an accuracy of approx. 1 mm and a range up to 200 mm, attached to the nozzle of the 3D printer. The sensor was positioned directly in front of the nozzle and could react

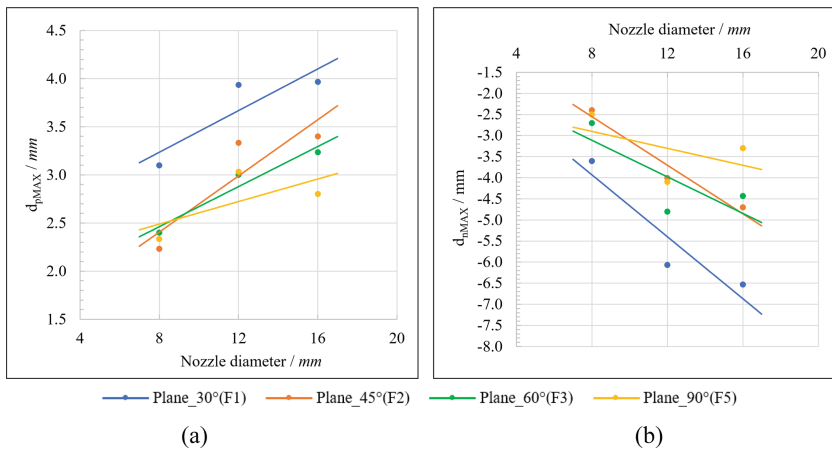


Fig. 3. Flatness errors variation of flat faces along with the nozzle diameter for different inclined angles: (a) maximum positive deviation; (b) maximum negative deviation.

instantly to the measurements via a wireless motion controller. Here, the data is collected, and continuously compared to a predefined, desired nozzle height. When deviations occur, a PID (proportional-integral-derivative) feedback system overrules the prescribed 3D print instructions (G-Code) and corrects the nozzle position in real-time.

The adaptive feedback system was demonstrated in a 250 mm radius cylinder wall printing. When the wall was printed with a conventional fixed increment in the z-height (Fig. 4a), deformations resulted in a significant deviation of the nozzle height, leading to poor layer placement and finally collapse. Using the feedback system ensured consisted nozzle position with respect to the working surface and a successful print of 50 layers (Fig. 4b).



Fig. 4. 3D printed cylinder walls without (a) and with (b) the adaptive feedback system (figures reproduced from [42]).

3.3 Postprocessing Operations: In Between to Production Steps

AM often results in undesirable level of precision in the surface finish and post-processing is required to bring the part into tolerance. Here the SC3DP technique [43] was applied to manufacture a doubly-curved, fully-reinforced concrete wall of $2.5 \times 0.18 \times 2.3$ m including manual placement of pre-bent horizontal and vertical reinforcement (Fig. 5). The first stage was to print the vertical wall, install reinforcement, and then to spray the vertical surface, prior to a troweling operation to smooth the surface. The initial print was 3D scanned so that the as-printed part could be used to generate the tool path for the second spray process.

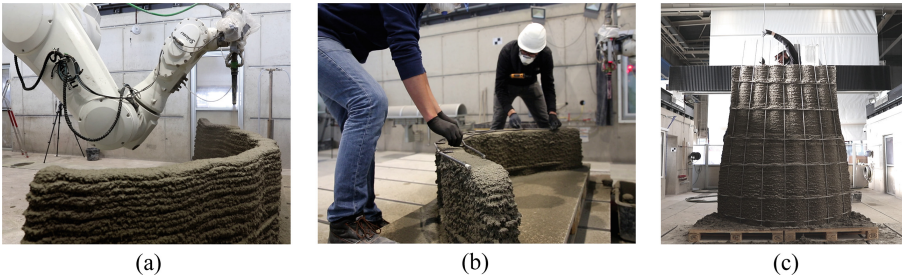


Fig. 5. SC3DP with reinforcement: (a) wall shotcrete 3D printing; (b) manual placement of the pre-bent horizontal bars; (c) threading in the vertical bars.

3D laser scanning and multi-view photogrammetry were used to generate 3D point clouds of the printed components. Data was acquired under different object conditions (dry/wet, with/without reinforcement, before/after surface finishing) in order to take possible conditions on real construction projects into account. Figure 6 depicts as-planned model of the demonstrator and data capturing in different steps using above mentioned techniques. For multi-view geometry a non-professional digital camera was used and 80 images were captured. Then, PiX4D software was used to align the images

and find the key points and perform the image matching. For 3D laser scanning, Leica P20 TLS was used to scan the object from 6 stations (2 stations before reinforcement and 4 stations on final product) with the average distance of 3 m between the scanner and the object. The average density of the point clouds is less than 2 mm. Considering localization of the instrument in each station, it takes ten minutes to run a scan on each station. As 3D laser scanning is a direct measurement of the points, no special post-processing is required.

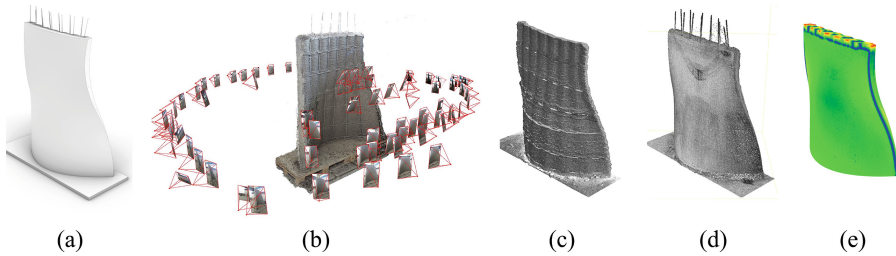


Fig. 6. Geometric inspection of a component: (a) 3D designed model of the wall; (b) photogrammetric block around the fabricated wall; (c) TLS data before reinforcement; (d) TLS data after reinforcement; (e) wall model colourised by C2C distance.

Eight targets were installed on different parts of the printing environment (cf. 2.2 co-registration) and their coordinates were also measured using the robotic arm in order to co-register the designed 3D model and the point cloud data acquired from the printed entity. TLS and photogrammetric point clouds as well as a 3D model were then co-registered using the 3D similarity transformation. Cloud to cloud (C2C) and cloud to mesh (C2M) distances were utilised to measure the deviations of the printed component from its digital twins.

3.4 Assembly Verification: After Installation

The COHESION pavilion at the University of Innsbruck (Fig. 1d, [44]) comprised of 47 unique components that were assembled into the installation of 6.20 m diameter, 2.70 m height and 12.2 tons of weight. Every layer in each part of the assembly constantly changed in height between 4.50 and 12.00 mm, generating material deposition issues. The challenge here was to verify that the whole assembly was within tolerance using two parallel options for larger-scale measurement: photogrammetry and 3D laser scanning.

For photogrammetry, a drone set-up with a DJI Phantom 4 Plus, 4 K sensor and predefined flight paths as well as Agisoft's Meta Shape for calculations was used. This produced 136 images in 1 h of flight and took approx. 3 days of calculation with 16-point cloud fragments, containing 13,304,966 points in total.

The 3D laser scanning with a Faro Focus S150 took approx. 1 h for 8 scans, which yielded varying numbers of points from 468,436–12,653,468 in each point cloud,

containing 23,924,383 points in total. The different amount of points in the individual scans was caused as some of the scans covered smaller areas on the pavilion exterior; the bigger ones covered more extensive areas (e.g. the interior). The surface area of the outer shell is approx. 88 m², resulting in a density of approx. 27 pts/cm² in the merged point cloud.

Once the orientationally adapted CAD model and the data sets from the two measurement approaches was aligned (Fig. 7a), a detailed data comparison (of 565 points) was achieved by measuring the distances between the CAD model and the scans. The precision of the photogrammetric data was reasonable for the general orientation and the build design evaluation, whilst the laser scanning was far more precise. A limit of 12 mm of deviation was defined to cull out problems of the closest point comparison. In the photogrammetric model, more than half of the points showed deviations above the limit (Fig. 7b). 110 points with more than 12 mm deviations (Fig. 7c) from laser scanning had to be visually checked, where 24 points actually had a deviation and others were at the boundary conditions of the structure which led to closest point comparison problems. 16 of the 24 points were located at the top-crease of the pavilion, which was a logical result because of the 3DCP process that filleted corners and creases. The 458 points with less than 12 mm deviations were visualized with diagrammatic 100 times scaled boxes at the location of the points of interest (Fig. 7d). As the deviation in neighboring areas was very similar, this led to the assumption that the elements still had a slightly offset position to the CAD model.

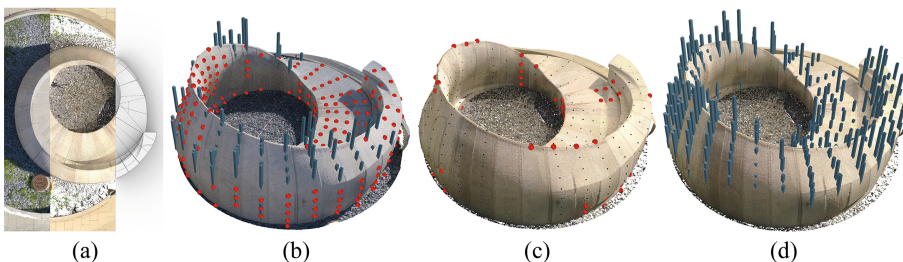


Fig. 7. Geometric inspection of an assembled structure: (a) overlay of photogrammetry, 3D laser scan and CAD model; (b) photogrammetry: points (marked in red) with deviations >12 mm, and points (marked in dark blue, values scaled by 100) with deviations <12 mm; (c) laser scanning: points (marked in red) with deviations >12 mm standing out especially on corners and creases; (d) laser scanning: points (marked in dark blue, values scaled by 100) with deviations <12 mm.

4 Results and Discussion

Table 1 presents the measurement system parameters from each case study. The structured light scanning method worked well at the scale explored, however the measurements were undertaken in a clean environment away from the manufacturing equipment. For measuring and verifying printed features, the method was robust. One

observation was that the increased number of scans will increase the cloud point processing operations, which might affect the measurement of larger parts and also for a larger component both 3D laser scanning and photogrammetry, proved feasible to capture the large amount of data via multiple stations within acceptable time period. In the case of the assessment of the assembly, these processes also identified the accumulation effect of the manufacturing errors on the conformity of an assembly.

Table 1. Factors related to geometric inspections in the four case studies.

Quality control action	Machine calibration	Adaptive feedback	Postprocessing assessment	Assembly verification
Inspection technique	Structured light scanning	1D laser ranging	3D laser scanning/Photogrammetry	3D laser scanning/Photogrammetry
Object scale	<0.5 m	Point	<3.5 m	<7.0 m
Object surface state	Wet	Wet	Wet-Dry	Dry
Ambient lightning condition	Indoor	Indoor	Indoor	Outdoor, sunny
Measuring distance	1.0–1.5 m	≤ 0.2 m	≥ 1.0 m	2.0–3.0 m
Measuring (point cloud) resolution	0.3 mm	1.0 mm	>1.0 mm	2.0 mm (laser scanning)/ 4.0 mm (photogrammetry)
Time consumption	For an inspection lot: 15–20 min for data acquisition; 2–4 h for data processing	Real-time	30–60 min for data acquisition; 2–5 h for data processing	60 min for data acquisition; 3 days for data processing
Cost of measurement equipment	3–6 k €	<0.2 k €	100 k € (laser scanning)/ 5 k € (photogrammetry)	50 k € (laser scanning)/ 7 k € (drone setup + software)

The 1D height measurement used for z-height correction on-the-fly was also promising. Key here is the speed at which the measurements can be processed into machine actions. With only linear distance measurements, this proved to be quite achievable. The method could be developed into 3D surface measurements to achieve 3D adaptive control for more complex applications of 3D curved geometries, which would then increase the required computational capacity.

Overall, the common technical challenges of different stage geometric inspection are time consumption (related to both data processing method and computational capacity), accessibility (inside of the structure), and ambient conditions (dirt, light, working space, etc.). Since 3DCP is usually used for creating bespoke one-off large-scale components and structures, it's critical that the printing parts are right-first-time, which can be achieved through material and process control. Geometrical measurement is a critical part of this process for establishing and checking machine precision, correcting the uncontrollable aspects of the process and for verifying form, either for a secondary process, to establish whether it is to specification or to determine the as built case.

It is likely that, rather than the traditional quality control based on random sampling parts, the bespoke nature of the components manufactured with 3DCP combined with less predictable process factors, is likely to lead to individual part verification. The automation of these quality control procedures throughout machine setup, printing and post-printing are somewhat inevitable, at least until 3DCP processes are demonstrated to be under control such that the uncertainties on geometric tolerance become insignificant.

5 Conclusions and Outlook

Additive Manufacturing with concrete offers more freedom in design and this has been demonstrated to lead to the manufacture of more bespoke complex geometries. 3DCP processes are currently not fully predictable because of a combination of material, environmental and process variables that are difficult to determine, isolate and mitigate the effects. The result is that the success of a print in terms of the geometrical conformance to the design drawing needs to be verified at every build.

Equally, it is likely that corrective action will be needed during manufacture to ensure a successful build, i.e. prevent collapse. Additional post-processing is will be important for many practical applications and so verifying the base print prior to the application of a more controllable second process is likely to become routine as a consequence. The expectation coming from this work is that more systematic use of measurement in the 3DCP manufacturing process will be a cornerstone of future systems.

Beyond pure quality control, digital data acquisition enables the creation of extensive databases in which production parameters such as nozzle size, feed rate, material, temperature and geometry etc. are recorded and correlated with the print result. With the participation of a larger research community in feeding such a database, it becomes increasingly possible through the use of sophisticated techniques such as artificial intelligence to make precise predictions about the future print results and potentially to make suggestions for optimized path planning and automated adjustment of the production parameters.

Acknowledgements. The case study in Sect. 3.1 was supported by: the UK Industrial Strategy Challenge Fund: Transforming Construction initiative (EPSRC grant number EP/S031405/1) and EPSRC Grant number EP/P031420/1.

The case study in Sect. 3.2 was part of a research project co-funded by a partner group of enterprises and associations, that consisted of (alphabetical order) Ballast Nedam, BAM Infraconsult bv, Bekaert, Concrete Valley, CRH, Cybe, Saint-Gobain Weber Beamix, SGS Intron, SKKB, Van Wijnen, Verhoeven Timmerfabriek, and Witteveen + Bos. Their support is gratefully acknowledged.

The case study in Sect. 3.3 was funded through the lower Saxony Ministry of Science and Culture and the Lower Saxony Technical Universities (NTH). The Digital Building Fabrication Laboratory was funded through the German Research Foundation (DFG). The Junior Professorship for Digital Building Fabrication is funded by the Gerhard and Karin Matthäi Stiftung. The measurements were carried out as preliminary studies within the framework of TRR 277 “Additive Manufacturing in Construction”.

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DIGITAL CONSTRUCTION: 3D Printing for Performative Houses

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<http://www.codesignlab.org/en/>

Abstract. The climatic change that is affecting widely our everyday life needs an adequate cultural and technological response in order to develop performative dwellings for sustainable living. The aim of this paper is to summarize the DIGITAL CONSTRUCTION [DC] applied research that we have developed for the Ance, the Italian National Association of Construction Companies. The research agenda is based on a multi-parametric approach to architectural design, integrating digital manufacturing technologies into the fabrication and construction process. Such approach investigates on the relation between industry 4.0 opportunities and the constraints of the world of building construction with the aim to bridge different knowledge through a series of concrete case studies. Therefore, the paper talks about the first [DC] design protocol for a modular house anti-seismic, robotically 3D printed and assembled on site using a mix of recycled materials.

With this premise, we have developed a design to manufacturing methodology able to control many aspects at the same time: environmental performances, structural efficiency and end ergonomic comfort.

Keywords: Digital manufacturing · 3D printing · Environmental design · Collaborative robotics · Micro-housing

The DC project, following the Hacking Gomorra research initiative [2], is investigating on the social and environmental role of digital fabrication technologies in the field of sustainable architecture. If a collaborative approach between human labour and advanced technologies is needed to minimise the critical effects of robots aided manufacturing process in the job market, we strongly believe that one of the future key factor will be related materiality and its lifecycle. As a matter of facts one of the major goals to achieve for our cities within the next 20 years will be to refurbish and/or to demolish most of the obsolete buildings realised between the 50's and the 70's. The issue of re-using demolition materials will be crucial to reduce CO2 emissions. This approach matches the agenda of the World Green Building Council (World GBC) that in year 2019 has issued a bold new vision for how buildings and infrastructure around the world can reach 40% less embodied carbon emissions by 2030, and achieve 100% net zero emissions buildings by 2050. Together, building and construction are

Technology Is the Answer, But What Was the Question? [1].Cedric Price.

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F. P. Bos et al. (Eds.): DC 2020, RILEM Bookseries 28, pp. 804–813, 2020.

https://doi.org/10.1007/978-3-030-49916-7_79

responsible for 39% of all carbon emissions in the world, with operational emissions (from energy used to heat, cool and light buildings) accounting for 28%. The remaining 11% comes from embodied carbon emissions, or ‘upfront’ carbon that is associated with materials and construction processes throughout the whole building lifecycle.

With this premise the [DC]’s vision to fully decarbonise the sector requires eliminating both operational and embodied carbon emissions integrating an environmental parametric approach into the architectural design using demolition and natural materials into digital manufacturing processes. Therefore, the use of digital manufacturing technologies will have a very important role in the construction process in order to provide on demand and customized dwellings optimizing resources (Fig. 1).

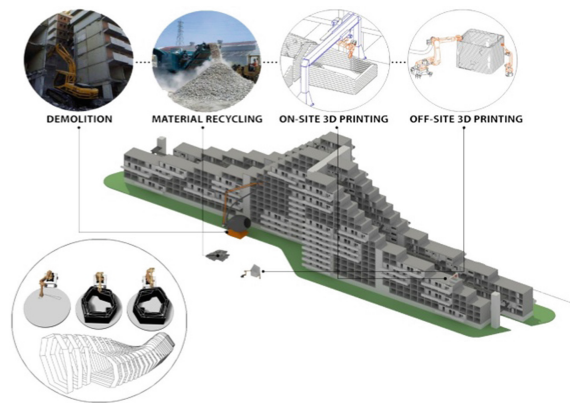


Fig. 1. De-construction and digital construction process from Hacking Gorrira project, courtesy of CODESIGNLAB

1 Research Method

1.1 Design Process

The design process is based on material optimization starting from modular portals that are further shaped based on environmental and structural analysis combined with architectural functions and ergonomic criteria. Each cross section is analyzed with a FEA software to obtain an optimal structural pattern based on material utilization. The construction process is based on a series of 6-axis robotic arms for the printing process and a team of human workers for the onsite assembly.

The idea of dynamic structures is related to the possibility of developing performative algorithms in order to customize standard solutions with a collaborative process that creates diversified site-specific configurations out of industrialized construction system.

With this premise, we have developed a design to manufacturing methodology able to control many aspects at the same time: environmental performances, structural efficiency and ergonomic comfort.

For the first 3D printing test, we have explored several semi-fluid material systems and possible mix from eco-concrete in order to realise the structural portal frames light and easy to transport. Our eco-concrete is based on the use a waste material, from demolition building, generating a new ecological semi-fluid mix. It is considered a process of physical transformation and customisation of the initial material system. The idea of using the demolition materials of some of the parts of existing buildings is based on metabolic approach to architecture as a living infrastructure. This includes a set of life-sustaining spatial transformations within the users of living architectural organisms.

At the same time, the assembly strategy proposes a fast deployment approach integrating an interlocking based system for the portals. The modular house is conceived as an off-grid system. Therefore, the global shape has been analysed to evaluate the solar radiation values for photovoltaic panels on the roof. The large-scale 3D printing has been proved an economic and versatile solution for standard construction elements produced both off site and on site. The proposed system investigates how to design incorporating multiple parameters to achieve an efficient architecture making full use of the potential of digital fabrication. On the other hand, 3D printing offers potential to customize each element according to multiple criteria. The interlocking portal system open to possible expansions of the structure providing a wide range of site-specific configurations.

At this stage, the limit of the research are based on the impossibility to develop a scale 1 to 1 full prototype because of the lack of resources and time. Therefore a series of smaller scale prototype (1: 50 scale) and 1 to1 details were 3D printed with a 3 axis Delta robot demonstrating the possibility of applying the same structural patterns with different material systems with the aim to convince our partner to invest more resources for further steps (Fig. 2).

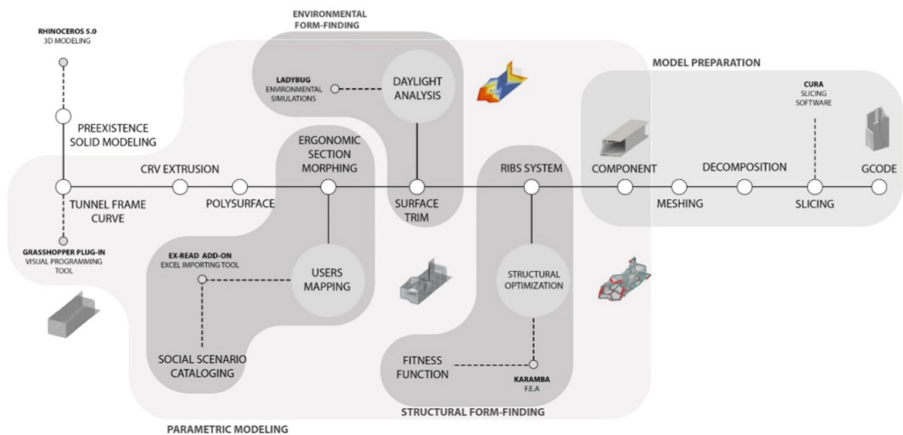


Fig. 2. Design process methodology, courtesy of CODESIGNLAB

1.2 Material Systems

The choice of material systems depends on an analysis of several experiences made on additive manufacturing technology with liquid materials for big scale 3d printing. One of the first applied research analyzed was developed by Behrokh Khoshnevis, within the project of Contour Crafting has experienced the use of fiber reinforced cement mortars, with “a compressive strength more than three times than the conventional concrete (10,000 psi, versus 3,000 psi)” [3]. Another interesting case study is named Amalgamma, a student’s team from the Bartlett University [4], that are developing a hybrid system, which uses the extrusion technology mixed to the powder bed technology. The ready mixed cement is extruded (FDM) by a robotic arm and the external surface is treated (from another tool on the same robotic arm) with granular powder, which mixed to a binder, can improve the strength and may allow more complex geometries. In addition, Rael R. and San Fratello V. of Emerging Objects, [5]. has experimented a polymer cement mortar, which is subsequently treated with sand powder.

These examples show us how the optimized cement mortar for 3d printing must be fibre reinforced and processed with chemicals (such as adhesives and hydrators) or natural substances (granular powders) to improve the structural strength.

In our case we have developed a 3D printing protocol that integrates into the mix some processed demolition concrete material (granular powder) into the final mix. The 3d printing concrete performances are well synthesized in by Le T.T. in “Mix design and fresh properties for high-performance printing concrete” [6] in which experimental procedures are identified four key characteristics:

1. Extrudability: the ability to transport the fresh concrete through a hopper and pumping system to a nozzle where it must be extruded as a continuous filament;
2. Workability: Conventional methods evaluating workability include slump, compacting factor and flow tests;
3. Open time: time of a cementations material has a relationship with its setting time
4. Buildability: of fresh concrete was quantifying as the number of filament layers which could be built up without noticeable deformation of lower layers.

1.3 Parametric Form-Finding

The form-finding processes for the model can be physically shaped and simulated through digital dynamic relaxation. The latter involves iterative calculations based on internal ergonomic, environmental slicing and structural ribs. Subsequently this informs the site/user specific ergonomics of the internal part of the components through a loft of prototypical sections. In this sense, the software becomes a user-driven design tool (Fig. 3).

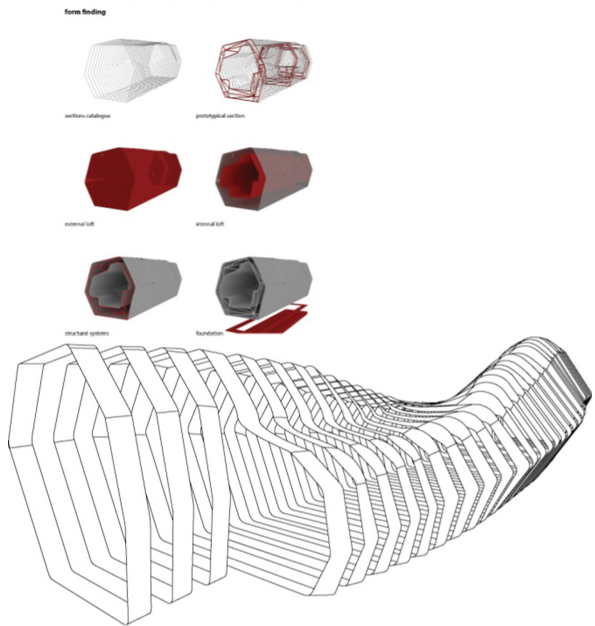


Fig. 3. Form finding, courtesy of CODESIGNLAB

1.4 Performative Testing/Simulations

The design process integrates a series of structural analysis to achieve an optimal design solution. Within the design environment, Karamba 3D is the software utilised for finite element analysis (Fig. 4).

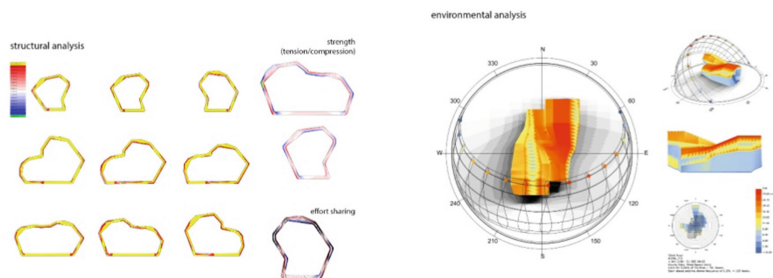


Fig. 4. Structural and environmental analysis, courtesy of CODESIGNLAB

The prototype is evaluated at a local and global level, to have higher control of the designed geometry. Firstly, each cross-section is drawn as a 2D polyline contour filled with an internal reinforcement pattern where each line segment is the edge of a triangle. This internal triangulation follows the functional architectural criteria of the prototype,

being denser where additional loads are expected such as near seating areas or on the base and lighter where higher mass is not preferable such as on the roof surfaces. The structural pattern is parametrically generated and for each triangle, the edge length and the vertex position are variables that can be modified to achieve an optimised solution. By automatically modifying these variables, with a custom algorithm, an infinite number of variations can be rapidly generated where the outer contour of the cross-section is constant and the internal pattern always different. Each one of these variations is analysed with a finite element model with defined thickness and material properties and by applying both self-load and an external uniform load. The final internal pattern geometry emerges from comparing the structural deformation and utilisation of different variations, achieving an optimal solution for weight, cost, and structural capacity. At a global level, the geometry is designed to accommodate multiple criteria and the final 3D mesh is analysed as a surface with a finite element model. The global geometry of the prototype is parameterized and its shape emerges by comparing the structural performances of different meshes. A back and forth, from global to local and vice versa, is integrated with a series of custom algorithms to achieve the desired compromise between the structural parameters and the other architectural functional criteria. In the last step, functional elements such as pipes, and electrical connections are added to obtain a model ready for printing. This model is also analysed to check the influences of non-structural openings in the overall structural capacity. This overall process is specifically developed for a digital construction workflow, where the fabrication parameters inform the structural capacity and an optimal compromise is achieved. The success of this first proposed prototype demonstrates the potential of this process and the advantages of material saving and structural optimization.

2 Results

2.1 Fabrication Process/Protocols

The fabrication process is based on a cement 3D printing robotic system that combines a 6 axis industrial robot, a rotary positioner, a semi-fluid extruder effector, a material pump and a series of additional hardware. The 6 axis industrial robot constitutes an affordable and efficient solution for the scale of the designed prototypes, due to its limited reachable space (maximum 4.00 m) an additional positioner is integrated as an external rotary axis to increase the overall fabrication space. The fabrication process is divided into two phases: an initial data preparation where all the fabrication parameters are digitalized and a second phase when the actual prototype is printed. The current research focuses only on the first phase, defining the fabrication steps and protocols that are required for 3D printing a large-scale cement prototype. Firstly, the prototype is divided into multiple cross-sections and each is printed separately and assembled on-site. Digitally, the cross-sections are simplified as curves that are additionally divided into multiple points; the points distribution defines the resolution of printing. Higher resolution increases printing time while lower resolution decreases printing time, an intermediate value is defined based on cost and fabrication time. During printing, the

tip of the extruder, mounted on the robot, will move from one point to another, defining the tool path. This tool path of the extruder is simulated within the design environment through a series of custom algorithms to monitor and evaluate collision detection, printing speed, and material quantity. The simulation integrates all the robotic system and it utilises an inverse kinematic approach to define the rotation of each robot axis at a specific point. By utilising this approach, it is possible to visualise a printing code and correct eventual anomalies and to generate a file for the robot. The final file is a source code that integrates the commands for all the machines that operate within the system, the relationship and communication between all the parts of the system is managed by this main source code file. Consequently, the fabrication process is defined completely in a digital realm and mistakes, errors and possible problems are resolved before starting the physical printing process, saving energy, material and time. Additionally, this fabrication process could be implemented as a factory standard where multiple industrial robots print different sections at the same, drastically reducing the fabrication time and reducing the overall costs and expanding the application of a digital construction approach (Fig. 5).

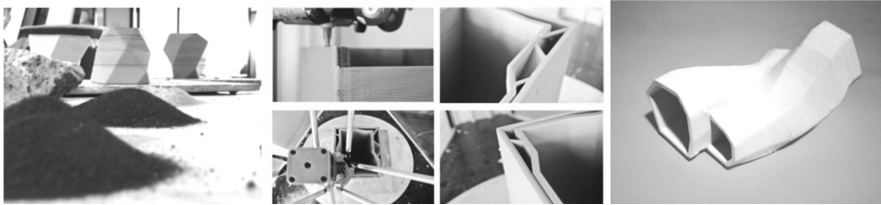


Fig. 5. Material mix and 3D printing process, courtesy of CODESIGNLAB

2.2 Robotic Assembly Systems/Protocols

The designed prototype is 3D printed in sections off-site and assembled on site with a collaborative effort of robots and human labour force. The sections are connected with an interlocking system to obtain a continuous surface, improving global stability and structural performances. This interlocking system is stabilised with additional steel cables. The steel cables run through the structural pattern of multiple cross-sections, and they are post-tensioned to create a cohesive structure. The assembly process starts by unloading and correctly positioning the cross-sections by a collaborative effort of humans and robots. Due to the large dimensions of the cross-sections, heavy duty 6 axis robots are utilised to assist the humans in the assembly tasks where precision is a key factor. After positioning the cross-sections, the human workers are responsible for adding the steel cables and installing all the additional functional elements (pipes, electrical cables, glazing...). The steel cables are gradually tensioned with the assistance of high pay-load robots until the target position and tension is reached. The human workers, constantly assisted by the 6-axis robots, do the final construction processes such as indoor and outdoor surface. This collaborative approach integrates both the high adaptability of human workers to unexpected events and the high strength and precision of robots.

Furthermore, a second fabrication and assembly strategy is investigated to minimise the component weight and to simplify the transport. Within this process, each cross-section is divided into brick-like components that can be printed with smaller robots and packed more efficiently. These smaller elements can be easily assembled on site with the aid of robots for lifting and positioning them. Each 6 axis robot could be equipped with a pneumatic gripper for functioning as a powerful arm to assist the human workers. Additional sensors could be integrated within the robotic system to achieve a more autonomous robot that can sense its environment and react to possible unforeseen events. This process will create a new concept of construction site, where digital and physical information are fused to increase the speed and the efficiency of the construction industry. In this new construction site, the human workers are the connection links between the digital and physical world, combining their material knowledge with the advantages of robots. Higher complexity could be introduced in buildings without increasing the overall costs, creating a new way of designing and constructing and opening up the possibility for free-form explorations (Fig. 6).

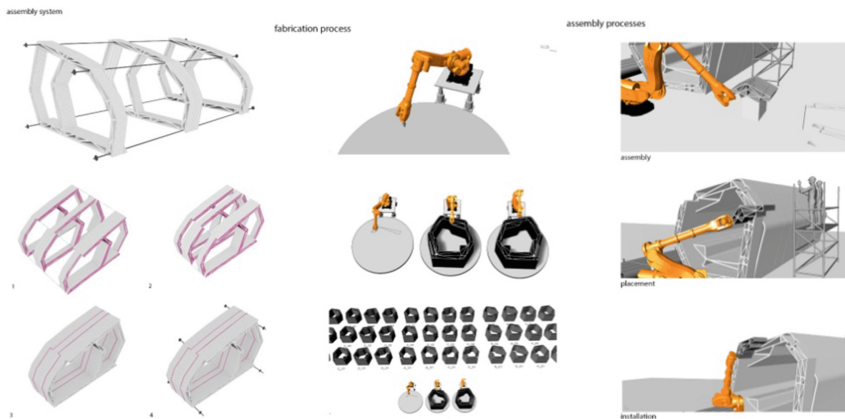


Fig. 6. Fabrication process, assembly system and robotic arm, courtesy of CODESIGNLAB

2.3 Scalability

The single prototype can be considered as a module of a larger housing complex. Multiple modules could be 3D printed off-site and then assembled with a stacking system to achieve complex overall configuration (Fig. 7).

Within this aggregation, the internal structural patterns of each cross-section will be designed to take in account the extra load to support. By generating a variation of space and structure, the final housing complex will emerge as a custom solution fitting the exact requests and condition of the final users, minimizing the on-site work and optimizing the construction process in a larger scale. The use of digital manufacturing technologies is functional to our approach based on the instrumentality of the housing system. Therefore, a catalogue of possible module configurations once assembled could generate a programmatic and social “mixture” of the building conceived as an open system (Fig. 8).



Fig. 7. Project digital construction, courtesy of CODESIGNLAB

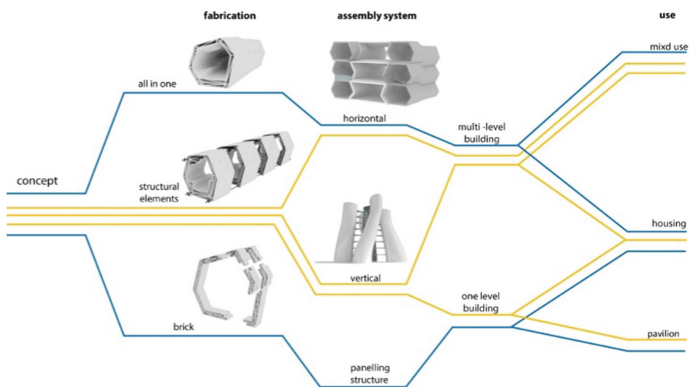


Fig. 8. Development process, courtesy of CODESIGNLAB

3 Conclusions

The DIGITAL CONSTRUCTION project is the result of a synergy between different knowledge and players from the world of building construction. For the first time in Italy entrepreneurs from construction companies together with material and digital manufacturing industries were concretely involved in a cross disciplinary initiative exploring the role of digital fabrication in designing and building performative architectural dwellings. For these reasons, we consider the [DC] project a crucial opportunity for a cultural shift in Italy from building to digital industry construction. In conclusion, the proposed 3D printed modular house can offer a faster solution compared to traditional construction methods, offering additional design freedom and tailor made ergonomic solutions. The environmental impact approach using waste materials from demolition into the 3D printing process will dramatically reduce CO2 emissions improving the environmental performances of architectural dwellings with the aim to reduce their energy consumption.

Acknowledgements. The research was financed by Ance Giovani, the Italian National Association of Construction Companies (under 40 entrepreneurs), under the guidance of former president Roberta Vitale. The first results of such research were presented (Rome-2017) at the XVIII Ance National Symposium titled “M4ttoni.0 – digitalising a traditional vocation”. The discussion involved experts from different sectors and companies such as Arup engineering, Mapei, ABB and H-Farm. The mid-results were presented at the Fidec the Italian Forum of construction (Milan-2018) and the SAIE 2018 Technologies towards Building and Built Environment 4.0 (Bologna – 2018). In year 2018 the DIGITAL CONSTRUCTION project has been published on the *Industria delle Costruzioni* (n 461) [7], review and on the *Sole 24ore* as a best practice on digital manufacturing for architecture.

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Extended Lattice Model to Simulate the Printing Process of 3D Printed Cementitious Materials

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Abstract. This paper reports an extended lattice model for printing process simulation of 3D printed cementitious materials. In this model, several influencing factors such as material and geometric nonlinearity are considered. Using this model, green strength of cementitious material is investigated, deformation and crack pattern can be derived, which is close to the experimental result. Subsequently, numerical analysis of 3D printing is conducted for the simulation about printing process. Imperfections arising in the printing process can be incorporated and two failure modes including the elastic buckling and plastic collapse can be simulated through this model.

Keywords: Lattice model · 3D printing · Material nonlinearity · Elastic buckling

1 Introduction

Over the past decades, 3D concrete printing (3DCP) gains much attention in the construction industry due to the cost reduction and production rate [1–3]. This technology gives capacity to construct the structures by layer-wise extrusion process without using formwork [4]. To search for the suitable printable materials and optimize the printing process, more than 30 research groups worldwide are currently engaged in the research about 3DCP.

In 2008, Thorpe and his co-workers [5, 6] from Loughborough University completed one of the first 3DCP programs named Freeform construction by constructing a gantry-based 3D cementitious materials printer and developing a high performance printable cementitious material. Printable materials should be sufficiently strong, stiff and stable to retain the shape and avoid large deformation under the weight of subsequent layers [7–9]. More recently, explorations have started into many aspects including the printable material compositions and printing scheme. A fundamental understanding of printable materials and printing process has developed via two parameters: “open time” for printable materials (open time is the period where the mechanical properties meet the printing requirement) and the “buildability” for the printing process (Buildability is that the object can be successfully built without failure and large deformation) [7, 10–15].

Albeit a steadily growing number of researchers active in the 3DCP research, numerical and theoretical models are still in their infancy. Roussel [19, 22, 23] investigated the rheological and thixotropic characteristics of cementitious materials and established the linear strength evolution with hydration time. An analytical model based on material rheology [19] was ultimately proposed to evaluate the printability of cementitious materials [16–20]. This analytical model, which has been experimentally validated, can predict the maximum number of printing layers considering the plastic collapse failure mode. Successive developments of this model can be found in the literature [5, 15–19, 22, 24]. The plastic collapse failure mode can be well predicted using such analytical models. But some issues still remain. The other failure mode (i.e. elastic buckling) is ignored in analytical models since the influence of structural geometry is not considered. Confronted with this research gap, a mechanistic model was proposed by Suiker [21] for the analysis of elastic buckling and plastic collapse. This mechanistic model was derived using a combination of energy theory, equilibrium equations and boundary conditions. The geometric imperfections generated during printing of a wall was included in the buckling model by decomposing the dimensionless deflection. Experiments were used to validate numerical results, which underestimated the total number of filament layers by 10%. Furthermore, the mechanistic model was limited to the straight wall structural geometry. To propose a more versatile model, Wolfs et al. [9, 25] investigated the mechanical properties of cementitious materials at an early stage and hardened stage through a uniaxial compression test and a direct shear test to derive the mechanical properties in numerical simulations. Based on the experimental results, numerical analyses of the green strength and the printing process of cementitious materials were conducted using commercial software ABAQUS [9]. The model yielded reasonable results, with 25% overestimation of the total number of filament layers compared to the experimental results. Importantly, by using this numerical model, the correct failure modes such as elastic buckling and plastic collapse were predicted. From the review of current research, it can be stated that all listed models show great progress in evaluating the buildability and printability of cementitious materials. However, some issues still exist in these models. For instance, most models ignore important influencing factors such as imperfections, plastic shrinkage, and creep, among others. A more reasonable numerical model is necessary for optimizing the printing process and guiding a real 3D printed project.

Lattice model, based on the discontinuous formulation, can avoid singularity-related issues in continuum-based numerical methods. Besides, the imperfection during the printing process can be easily implemented in the lattice model. Herein, the lattice model is utilized as the basic model to do specific improvements to meet the requirements of 3DCP numerical analysis.

In this paper, the extended lattice model is proposed for numerical analysis of the printing process of 3DCP. The proposed model takes the geometric and material nonlinearity into account. The model is used to simulate the green strength and the printing process. This paper can be divided into 3 main parts. In the first section, basic theory of the lattice fracture model is briefly introduced and some improvements on the lattice model for considering nonlinearity and non-proportional loading are explained for 3D printing simulation. In the second part, the green strength of cementitious

material is simulated for the calibration of local mechanical properties of 3D printed concrete. Finally, using the obtained input parameters, the simulation of the 3D printing is performed, showing the capability of the model to capture the typical failure modes.

2 Model Development

2.1 Lattice Model

In the lattice fracture model, the material is discretized by a network of Timoshenko beam elements, which are constituted by the random nodes in a limited domain through the Delaunay triangulation [26]. The schematic view of lattice model generation for 3D printing can be found in Fig. 1. In lattice model, the Timoshenko beam element is generally used to model shear deformation considering the low ratio of length and height of the beam elements in the lattice model.

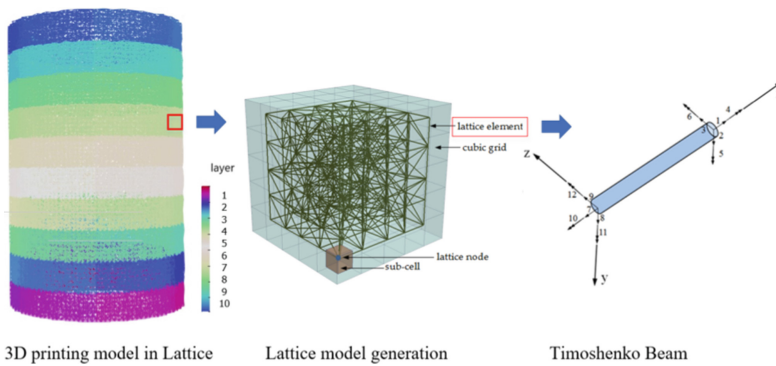


Fig. 1. Schematic view of lattice model generation for 3D printing

In lattice fracture model, the element strength and stiffness are obtained by calibration of experimental data [26, 28, 29]. Using these mechanical properties, a set of linear elastic analysis is performed through the calculation of stress distribution for each element subjected to an imposed particular load. The element with the highest stress/strength ratio is regarded as the critical element and removed from the lattice mesh, thereby introducing a small crack [26]. Once the critical element is found, the mechanical properties change and the global stiffness matrix is updated due to the damage. The step-by-step removal presents the initiation and propagation of the crack, finally, crack pattern of the lattice model could be obtained. Meanwhile, the displacement of the model, calculated by scaling factor and prescribed displacement, determines the load-displacement curve of the model.

Based on the Timoshenko beam theory, the element is a lattice beam of uniform cross-section and can transfer the uniaxial force, shear, bending and torsion [27]. The stress for the lattice element is calculated by the following equation.

$$\sigma = \frac{F}{A} + \alpha \frac{(|M_i|, |M_j|)_{\max}}{W} \quad (1)$$

Where F is the normal force for the lattice beam element, M_i and M_j are the local bending moment in local coordinate system, A is the cross-sectional area of an element, and $W = \pi D^3/32$ the section modulus of an element (D is the diameter of the circle area). The coefficient α is the bending influence factor which balances the final failure mode in which either force or bending plays a dominant role. According to previous research [26, 28, 29], the value of the bending influence factor is set to 0.05.

2.2 Extended Lattice Model

The lattice fracture model for fracture analysis of cementitious materials has been proposed by Schlangen [26, 28, 29]. This model is generally based on the sequentially-linear analysis procedure, and each element has brittle behaviour.

In lattice fracture model, the element step wise constitutive relationships are calibrated by fitting the global load and displacement curve to represent elastic-plastic behaviour (see Fig. 2). In every analysis step, loading or displacement is increased until one beam in the model has the stress/strength ratio equal to one. This critical element weakens and reduced stiffness is set to the element for the next step calculation. When reaching the last step in the constitutive relationship, this beam is removed from the system. The loading procedure is increasing until a predefined stop criterion (e.g. load or displacement).

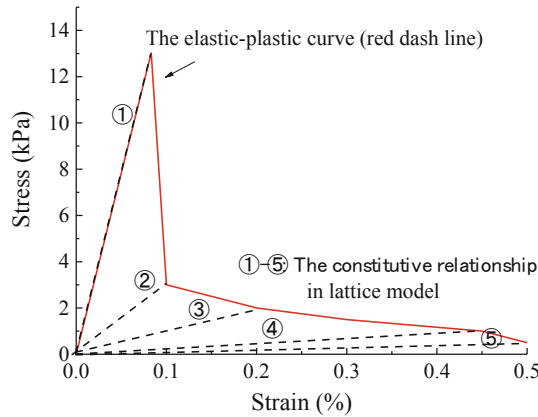


Fig. 2. The elastic-plastic constitutive relationship in lattice model

The second improvement is related to non-proportional loading. After extrusion, the self-weight of previous layers remains in the system, resulting in an internal force among in the lattice elements. When the following layer is printed, the prescribed load

increment results in failure of additional elements, which causes stress redistribution. To overcome this issue, the improved sequentially linear solution, proposed by the Eliáš [30], is incorporated into the lattice model.

Another improvement is the consideration of the geometric nonlinearity. Apart from the removed or degraded elements, the nodal displacements' variation in the lattice system also results in the disequilibrium force. After occurrence of the force, a sequentially linear redistribution process of stress release takes place until a static equilibrium state reaches.

Taking these influencing factors into consideration, the extended lattice model is used for simulation of 3D printing.

3 Numerical Analysis

The numerical analysis of 3DCP is investigated in two steps using the extended lattice model. The first step concerns calibration of the local mechanical properties by simulating the compression test. A case in point, the element mechanical properties for the simulation of green strength in 30-min is as shown in Fig. 2. In the second step the extended lattice model is utilized to simulate the structural behaviour during the printing process and research the failure-deformation mode.

3.1 Compression Test

The extended lattice model is used to analyse the green strength (the compressive strength obtained from such mortar cylinders in fresh state is commonly called green strength of the tested material) and deformation characteristics of fresh cementitious material, relying on the experimental results from Chen et al. [12, 13].

In their experiment, cylinder specimens with diameter of 33.5 mm and height of 67.5 mm are utilized for the investigation of green strength. In the numerical analysis, the displacement in vertical direction is applied to the top of edge of the cylinder, which corresponds to 15% vertical strain. The bottom is simply supported in vertical direction. The step-wise constitutive relationship is utilized to represent the elastic-plastic mechanical constitutive relation in extended lattice model.

The numerical analysis for cementitious materials is performed for each stage in the experimental program. The calibrated mechanical properties are as shown in Table 1. The resulting load-displacement diagram in loading direction is compared with the experimental results, see Fig. 3. The simulation results (in solid line) agree well with the experimental finding (in dash line). Besides, the global deformation of the specimen ($t = 40$ min) and the crack patterns for the sample ($t = 4$ h) keep the same with the experimental diagram. Therefore, the extended lattice model is deemed possible to model the green strength and deformation characteristic of fresh cementitious materials.

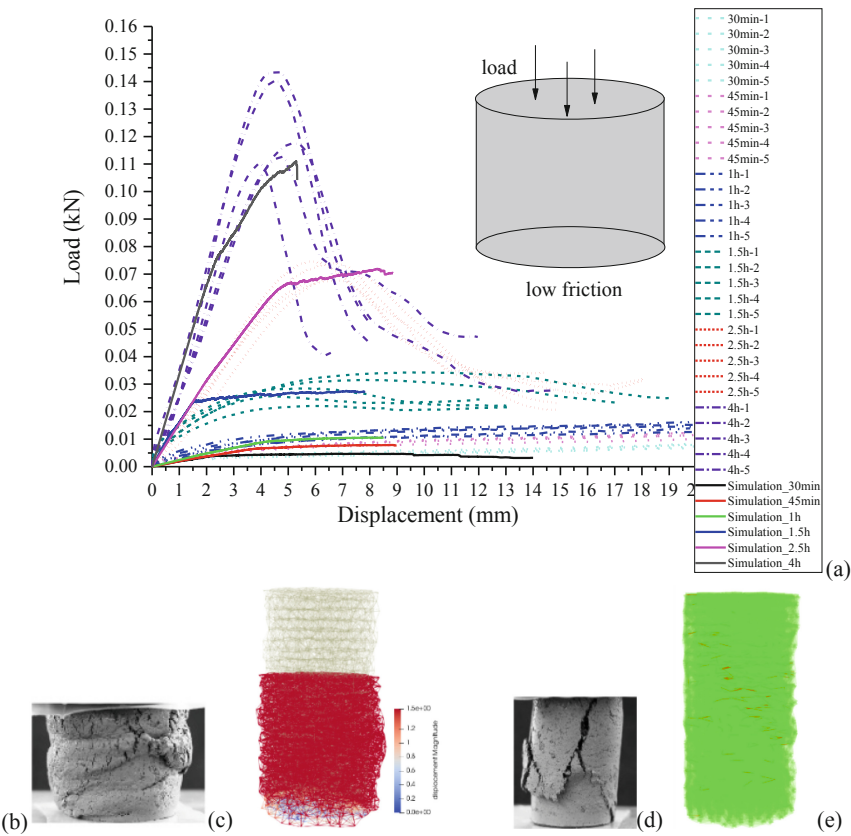


Fig. 3. The comparison between the numerical result and experimental results (a) load-displacement curve (b) Deformation from literature [13] (c) Deformation in numerical analysis (d) Crack pattern from literature [13] (e) Crack pattern in numerical analysis

Table 1. Calibrated element mechanical properties in lattice model

Time/min	Segments	Part 1 (kPa)		Part 2 (kPa)		Part 3 (kPa)		Part 4 (kPa)		Part 5 (kPa)		Part 6 (kPa)	
		E	F_c	E	F_c	E	F_c	E	F_c	E	F_c	E	F_c
30	6	161	8	33	8	19	8	13	8	10	8	8	8
45	6	157	13	49	13	29	13	21	13	16	13	13	13
60	5	197	18	67	18	40	18	29	18	23	18		
90	6	1461	50	222	50	120	50	82	50	63	50	13	13
150	4	1261	128	478	128	295	128	213	128				
240	2	2705	240	1200	240								

3.2 Printing Process

The overview of printing process parameters for cylinder and wall structure are listed in Table 2. In both numerical analyses, the bottom layers are taken as fixed, assuming high friction in printing bed. Each node in the extended lattice model has gravity representing the self-weight of the printable materials. The element mechanical properties of each layer are assumed to be constant, which should be calculated during the analysis based on their age in the printing process, for instance, after 5 layers, the initial layer will be 32.5 min old and use the corresponding mechanical properties of that age, while the last printing layer should be 30 min old, and so on. Since in this paper, the model time for the designed project is less than 5 min, the strength and stiffness are assigned as constant.

Table 2. The input parameters for the models

	Parameter	Value
Wall structure	Wall thickness (w)	12 mm
	Wall length (l)	200 mm
	Height for each layer (h)	7 mm
	Printing speed	30 s/layer
Cylinder structure	Heart radius	62 mm
	Thickness for each layer	13 mm
	Height of each layer	6 mm
	Printing speed	30 s/layer

For the wall structure, two imperfections are introduced to the wall structure model to investigate the imperfection influence on the final failure mode, in which 8th and 10th layers are subjected 1.5 mm horizontal shift.

Two numerical models are investigated to study structures with different geometry and the impact of imperfections during the printing process. Figure 4 shows the initial structure and the deformed model towards different printing shape. For the cylinder structure, due to the restrained deformation in the radial direction, a tendency of cylinder buckling occurs, which is a combination of elastic buckling and plastic collapse. The subsequent printing layers increase the element stress and strain due to the increasing self-weight in the model. At this point, some elements meet the failure criteria and are removed from the model. Therefore, the system becomes unstable and the tendency for elastic buckling are more obvious. For the wall structure, a more obvious elastic buckling can be observed due to the horizontal shift in the 6th and the 10th layer. After the 12th layer, the imperfections cause the system to lose its capacity to bear the load from subsequent printing layers and the model eventually fails.

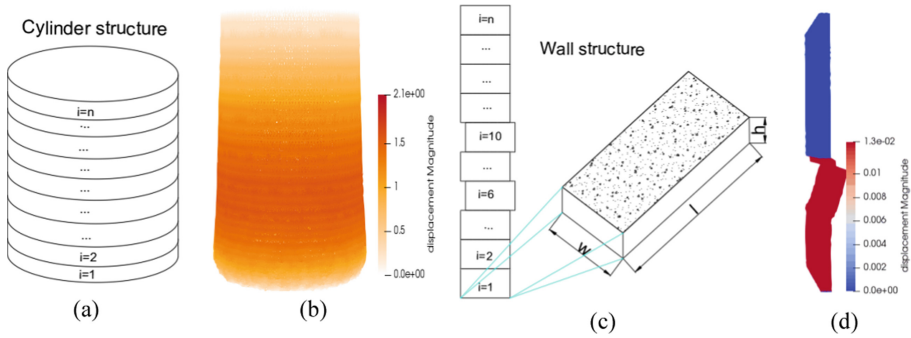


Fig. 4. (a) Hollow cylinder (b) Failure mode about the hollow cylinder (c) Wall structure (d) Failure mode about the wall structure

4 Conclusions

In this paper, an extended lattice model is proposed to simulate the green strength of cementitious materials, in the range of 30-min to 4-h after adding water. Subsequently, the printing process is simulated using the input parameters derived by the calibration of the compression test. Based on the presented results, the following conclusions can be formulated.

- The extended lattice model is able to model the green strength and deformation characteristics of fresh cementitious materials;
- The structural behaviour of cementitious material during 3D printing can be simulated and the corresponding failure-deformation mode can be derived using this model.
- Finally, it may be concluded that the extended lattice model is suitable to simulate 3D printing of concrete. As further work, the model should be validated by comparison to printing experiments. Besides, more influence factors such as plastic shrinkage will be introduced into the model and the model will be further utilized as a numerical tool for the optimization of 3D printing.

Acknowledgements. Ze Chang would like to acknowledge the funding supported by China Scholarship Council under grant number 201806060129.

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Quality Assessment of Printable Strain Hardening Cementitious Composites Manufactured in Two Different Printing Facilities

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Abstract. Over the past few years, several studies have shown the potential of three-dimensional concrete printing (3DCP) for applications in building and civil engineering. However, only a few studies have compared the properties of the fresh printing material and the quality of the printed elements from different printing facilities. Variations in the manufacturing conditions caused by the mixing procedures, the pumping device and the nozzle shape and/or dimensions may influence the quality of the printed elements. This study investigates the differences in the fresh and hardened properties of a printing material tested in two different printing facilities. The pump pressure and temperature experienced by the printing material during the printing session are monitored real-time. Hardened properties are measured for the printed elements, such as the bending capacity, the apparent density, and the air void content. The research shows that two different printing facilities may result in printed elements with relative differences in flexural strength and volumetric density of 49% and 7%, respectively.

Keywords: SHCC · ECC · Quality control · 3D concrete printing

1 Introduction

Three-dimensional concrete printing (3DCP) is one of the additive manufacturing (AM) methods currently under development for applications in the building industry. Over the last decade, extensive research has been conducted on this new technology, as it has the potential to lead to significant economic benefits by speeding up the production process, and by reducing the formwork costs. It also offers promising environmental advantages, e.g., by minimizing the use of material through the application of structural shape optimization. Moreover, benefits have been identified in regard to the increase in freedom of

design and the decrease of hard physical labour [1–3]. Current research focuses, among others, on the printing process, on the development of suitable concrete mix designs, and on the fresh and hardened material properties of the printed concrete. Collaborative projects between universities and industry have already resulted into several printed concrete structures being applied in practice, such as 3D printed concrete bridges [4].

One of the challenges within the development of 3DCP is the improvement of the limited ductility of printed mortars. Traditionally, steel rebars are used to transfer tensile stresses in concrete and to increase the ductility during fracture, in accordance with building regulations on structural integrity and safety. However, for 3D printed concrete the incorporation of traditional steel rebar reinforcement is not straightforward [5,6], as a result of which several alternative solutions have been considered. Firstly, the application of passive reinforcement steel has been suggested, for example, by using reinforcement meshes [7], by connecting the printed concrete element to an external steel reinforcement framework [8], or through the application of an advanced printing nozzle that lays down a steel wire within the concrete layer during its printing [9,10]. Secondly, post-tensioned, pre-stressed reinforcement may be applied. In this method, the concrete elements are printed without reinforcement; instead, the reinforcement is placed in the slots of the printed elements after assembly, and is subsequently pre-stressed in accordance with design specifications [4,11].

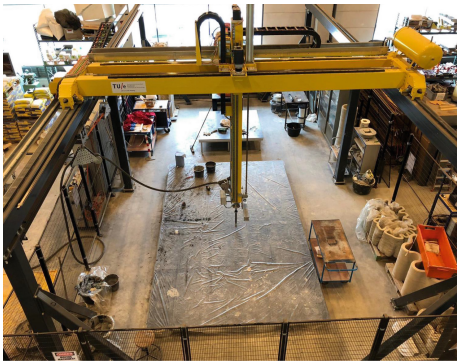
Another option of reinforcing fresh concrete in 3D printing processes is through the application of fibre-reinforced cementitious composites. A promising printing material that is characterized by both a high ductility and a high tensile strength is a strain hardening cementitious composite (SHCC). The mechanical performance of such composites is achieved by a tailored bond interface between the matrix and the fibre. Accordingly, the fibres are able to bridge a microcrack and transfer the tensile load that created the crack. Due to this bridging effect, the actual microcrack remains stable and does not grow into a macrocrack upon a further increase in loading. Instead, the stress is redistributed, which may induce a microcrack elsewhere in the concrete element that subsequently is also bridged by the fibre reinforcement. This repetition of the formation and bridging of microcracks effectively results in a strain hardening behaviour of the concrete element [12]. Since SHCCs are characterized by a relatively high tensile strength and a reliable ductility, it's worth to consider them a candidate for 3D concrete printing. Indeed, several studies have recently demonstrated the potential of this composite in 3D printing applications [13–16].

Preliminary research conducted at the Delft University of Technology and Eindhoven University of Technology has indicated that the printing settings utilized may have a significant influence on the final mechanical characteristics of the printed element. For example, relative differences up to 29% were found for the compressive strength obtained from specimens printed with the same mixture [6,14]. Since the mechanical performance of the SHCC strongly depends on an optimal balance of the matrix and fibre properties, small deviations in the printing process may have a substantial influence on the effective mechanical behaviour of the composite. This research investigates the influence of the

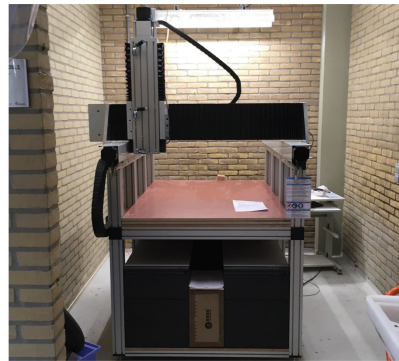
printing facility on the mechanical properties of hardened SHCC specimens manufactured by 3D printing. Accordingly, printing sessions were conducted with two different printing facilities, one located at the Delft University of Technology and one located at the Eindhoven University of Technology. The mix design, mixing procedure and printing routine were kept the same, and the temperature and pumping pressure were monitored during the printing session. After hardening, the printed elements were subjected to a three-point bending test with crack mouth opening control in order to characterize the fracture response and determine the fracture properties. Further, the apparent density was measured and the air void content was analysed.

2 Printing Facilities

The printing facilities at the technical universities of Eindhoven and Delft use a gantry system for creating the contour of the printed elements. The gantry systems in Eindhoven and Delft are illustrated in Fig. 1, and are able to print volumes of $[9 \times 4.5 \times 2.8] \text{ m}^3$ and $[1 \times 0.6 \times 0.35] \text{ m}^3$, respectively. The printing facilities are equipped with a mixing device and a pump, which are connected to a 5 m hose provided with a down flow nozzle. The hose has a diameter of 25 mm, and the nozzle has a rectangular cross-section of $[40 \times 14] \text{ mm}^2$.



(a) Eindhoven $[9 \times 4.5 \times 2.8] \text{ m}^3$



(b) Delft $[1 \times 0.6 \times 0.35] \text{ m}^3$

Fig. 1. Gantry system used in both printing facilities.

The mixing devices are both of the planetary type, but differ in volume capacity, engine power and operating speed. The mixing device in Eindhoven uses a TMV 75 pan mixer fabricated by Van der Zalm Nuth B.V., and is characterized by a capacity of 75 litres, an engine power of 2.2 kW, and a single rotational speed. In Delft, an A120N Hobart pan mixer is used, characterized by a volume capacity of 12 litres, an engine power of 0.27 kW, and three rotational speeds. Figures 2(a) and 2(b) illustrate the mixers used in both facilities. Due to the different specifications

of the engine power and printing volume, the mixing procedure in Delft was carried out in 7 batches of 3 litres each, while in Eindhoven a total volume of 28 litres was mixed in one batch. The pumps used in Eindhoven and Delft are an M-tec duo-mix connect and a PFT Swing L, respectively. The main differences between these pumps relate to the design of the rotor/stator and the mixing paddles that collect the material from the reservoir and push it through the rotor/stator. The pump components are illustrated in Figs. 2(c)–2(f).

3 Methodology

3.1 Materials and Specimen Preparation

The mix design used in the research has been developed recently Delft University of Technology, see [14] for more details. The specific composition can be found in Table 1.

Table 1. Mix proportion [kg/m³]

Raw materials	XVA3PVA20
CEM I 42.5	259.2
Blast furnace slag	604.9
Limestone powder	894.1
PVA fibres (Kuraray REC15)	26
Viscosity modifier admixture (VMA)	5.1
Superplasticizer	17.3
Water	345.6

The mixing procedure adopted in Delft was as follows:

- All dry materials were mixed for two minutes at a relatively low rotational speed of 60 rpm.
- During approximately one minute, water mixed with a superplasticizer was added.
- Next, the wet powders were mixed for two minutes, whereby a significant change in the mixture’s viscosity was observed.
- The dough-like mixture was further mixed for four minutes at a moderate rotational speed of 124 rpm.

The same mixing procedure was adopted in Eindhoven. However, due to the larger material volume and the use of a single rotational speed in the mixing device, the mixing time after the inclusion of the liquid ingredients was taken somewhat longer in order to achieve the same mix consistency as in Delft.

Initially, a single layer filament was printed at different speeds and constant pumping pressure, whereby the width of the filaments was measured to select



(a) Mixer in Eindhoven.



(b) Mixer in Delft.



(c) Pump paddles in Eindhoven



(d) Pump paddles in Delft



(e) Rotor/stator in Eindhoven



(f) Rotor/stator in Delft

Fig. 2. Comparison of the components of the printing facilities used at the Technical Universities of Eindhoven and Delft.

the optimal printing speed. Subsequently, two to three objects were printed with a height of five layers. The objects were kept on the printing table for 24 h, after which they were cured in water for 13 days. Subsequently, specimens of $[40 \times 40 \times 160] \text{ mm}^3$ were sawn from the hardened object, see Fig. 3, which were subjected to mechanical testing the next day (day 14).

3.2 Fresh State

During the printing session, the pressure in the hose and the temperature of the printing material were monitored continuously. Pressure drops may indicate potential failures in the extruded material due to the development of large air pockets, and temperature changes in the printing material may lead to significant alterations in its rheological properties and hydration speed. The pumping pressure was measured by installing analogical manometers directly behind the pump and just before the printing nozzle. The pressure measured by the sensors was recorded and the values were read off after completing the printing of the object. The heat development was monitored by means of two thermocouples installed on the manometers. Accordingly, the temperature reached in the printing facilities could be determined, and the origin of the heat generated during the pumping process could be identified.

3.3 Fracture Behaviour

The fracture behaviour of the hardened specimens was determined by means of a Crack Mouth Opening Displacement (CMOD) test: a 3-point bending test on notched beams in which the load point displacement is controlled by the gradually increasing opening of the notch, known as the CMOD value. All the tests were performed on an Instron universal test rig of the Eindhoven University of Technology. Initially at a crack mouth opening rate of 0.05 mm/min until an opening of 0.1 mm was reached. The test was continued at 0.10 mm/min of CMOD until the opening reached 2.6 mm at which point the test was discontinued. The applied CMOD experiment is a scaled down version of the test detailed in EN 14651 [17], to the size of beams used for the characterization of cementitious mortars ([i.e. $40 \times 40 \times 160] \text{ mm}^3$, cf. EN 196 [18]). This corresponds to a scale factor of approximately 0.27 and results in specimen dimensions that are more appropriate in the context of 3DCP. The bending test span was 130 mm. A 3 mm wide, 7 mm ($\pm 0.5 \text{ mm}$) deep notch was sawn into each specimen, leaving an effective section height at the notch of $h_{sp} = 33 \text{ mm}$. More extensive descriptions and a discussion on a potential size effect of this scaled-down CMOD test are provided in [19].

Specimens were sawn with an accuracy of $\pm 2 \text{ mm}$ from rectangular objects printed in Eindhoven ('E') and Delft ('D'). The specimen length corresponded with the filament printing direction, indicated as direction I. Figure 3 and Table 2 provide an overview of printed objects, obtained specimens and direction definitions. In the majority of specimens, the notch was applied across the filament width, in direction II. These specimens were labelled $I\alpha$. In some additional

D-specimens the notch was applied in direction III to study potential directional effects associated with the subsequent 90° rotation of the specimen during testing. These were named $I\beta$.

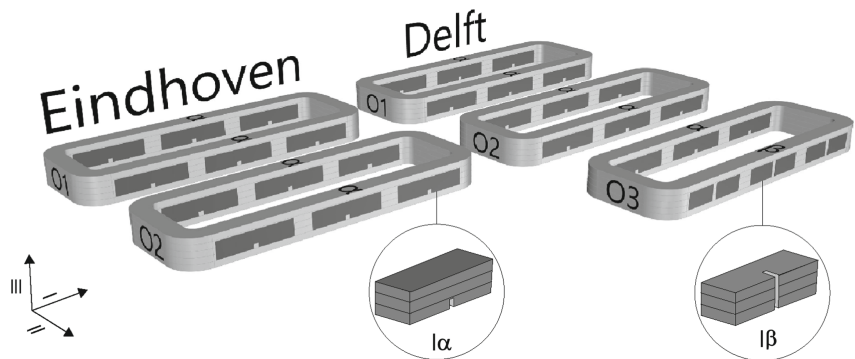


Fig. 3. Printed objects in Delft and Eindhoven with indicated specimen orientations $I\alpha$ and $I\beta$.

Table 2. Number of CMOD experiments and specimen orientations of the test programs performed.

	Eindhoven	Delft
Printed object 1 (O1)	6× CMOD-E- $I\alpha$	6× CMOD-D- $I\alpha$
Printed object 2 (O2)	6× CMOD-E- $I\alpha$	6× CMOD-D- $I\alpha$
Printed object 3 (O3)		3× CMOD-D- $I\alpha$, 3× CMOD-D- $I\beta$

3.4 Apparent Density and Air Void Content

The apparent density of the hardened specimens was assessed by measuring their weight and volume after the CMOD test. Based on the apparent density of the SHCC, the printing quality can be estimated. Additionally, a single core of 13.6 mm diameter was drilled from one object printed by the facilities in Delft and Eindhoven. This core was subjected to a micro-computed tomography scanning procedure (μ CT-scan). An acceleration voltage of 130 kV and beam current of 220 μ A were applied. The pictures obtained from the scans were created from an average of two radiographs with an exposure time of 0.5 s, each generating a total of 1441 pictures. In this way, pictures with a resolution of 8.33 μ m/pixel were obtained.

The software phoenix datos | $\times 2.0$ was used for reconstructing the three-dimensional specimen volume. The software centralizes the radiographs generated during the scan. Additionally, a beam hardening correction of 8 was used to correct for artefacts. With the help of the software VGStudio MAX 2.0, the image stack from the top and the right side view were obtained from the three-dimensional specimen volume and a median filter of 3 pixels in all directions was applied to the images. For analyzing the air void content and distribution in the image stack, the software ImageJ was employed. A grey value threshold was imposed in order to distinguish and isolate the air voids from the original images. In the new images of the void distribution, the size and content of the air voids with an area bigger than 40 pixel^2 and a circularity between 0.3 and 1.0 were counted. These filter values were applied to minimize the effect of the voids surrounding the fibres.

4 Results and Discussion

4.1 Assessment of the 3D Printing Process

The variation in temperature and pump pressure, as measured during the sequential printing of all objects, is summarized in Figs. 4(a) and 4(b) for the 3D printing facilities in Eindhoven and Delft, respectively. The pressure values obtained from the manometers installed close to the nozzle turned out to be very low, and therefore could not be read with sufficient accuracy. The pump pressure measured in the Eindhoven 3D printing facility on average is smaller than the pump pressure measured in the Delft 3D printing facility. Such pressure differences may be ascribed to various effects, such as differences in temperature, air void content, and alterations in static pressure height caused by moving the hose during the 3D printing process. In both printing facilities, the temperature rose from the moment the printing process started, whereby after some time a constant, stable temperature was reached.

In Eindhoven, the measuring of the pump pressure started from the very beginning of the 3D printing process, i.e., as soon as the material was pumped through the system, while in Delft the measuring started after the printing of 1.5 layers. This explains why the initial temperatures measured at the nozzle and in the pump are slightly different in Figs. 4(a) and 4(b). Observe further that the temperature of the printing material used in Eindhoven went up to 35°C , while in Delft the maximal temperature was approximately 27°C . This rise in temperature is believed to be due to frictional effects between the rotor and the inner part of the stator. Moreover, the observed difference in temperature rise between the two printing facilities can originate from the geometries of the rotor/stator, as has been illustrated in Figs. 2(e) and 2(f). It can be further observed that the temperature at the pump is higher than at the nozzle, which is due to heat being dissipated during material transport through the hose. In general, a printing material used in relatively long printing sessions is clearly exposed to a significant temperature increase, which will change its rheological

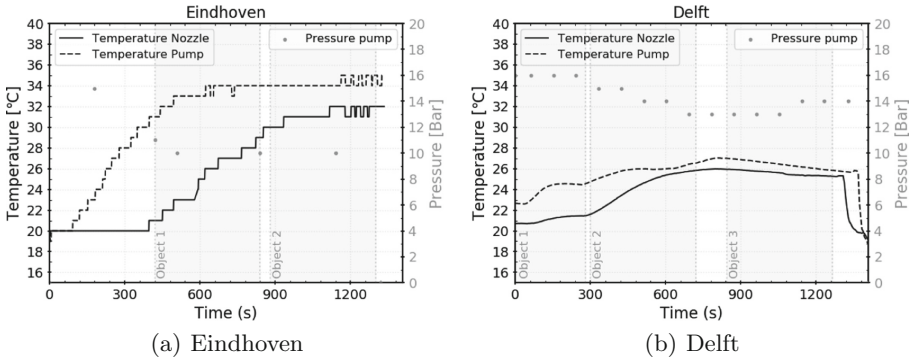


Fig. 4. Temperature and pressure profiles measured during the sequential printing of the objects.

properties, such as the buildability, see [20] for more details on this aspect. It is also noted that a temperature increase of the fresh printing material can accelerate water evaporation, which eventually might cause cracking due to shrinkage.

4.2 Failure Response in CMOD Test

The obtained flexural strength vs CMOD value curves are presented in Fig. 5. On the horizontal CMOD axis, the values of 0.135 mm, 0.405 mm, 0.675 mm, and 0.945 mm have been indicated, corresponding to 0.27 times the so-called CMOD₁ to CMOD₄ values as predefined by the EN 14651 [17]. Table 3 lists the average values of the (residual) strength parameters derived from the CMOD test: f_{LOP} is the Limit of Proportionality as defined by [18]; f_t is the maximum flexural strength; $f_{R,1} \cdot 0.27$ and $f_{R,3} \cdot 0.27$ are the residual strengths at the predefined CMOD values CMOD₁ and CMOD₃, respectively. In addition, the classification according to the fib Model Code 2010 [21] to characterize the residual strength is given, which is determined by the ratio of $f_{R,3} \cdot 0.27 / f_{R,1} \cdot 0.27$ (also provided in the table).

Figures 5(a) and 5(b) depict the results of the specimens sawn from the first object printed in Eindhoven and Delft, respectively. It can be seen that, after the initial stiff response that lasts until crack initiation, the load increases to a maximum that is reached at some point between the CMOD₁ and CMOD₄ values (i.e. strain-hardening), depending on the individual specimen. After reaching the maximum strength, the flexural stress gradually drops with deformation, showing a rather ductile softening response. The failure behaviour can clearly be ascribed to the bridging of the cracks by the fibres. Remarkably, the average maximum flexural strength f_t of the Delft specimens is 38.4% higher than that of the Eindhoven specimens. For the specimens sawn from the second object printed, this difference is even larger, namely 51.4%, see Figs. 5(c) and 5(d). The residual strength classification of the Delft specimens is also slightly better,

ranging from ‘d’ to ‘e’, while the Eindhoven specimens vary from ‘c’ to ‘e’ (details on this classification can be found in [21]).

Table 3. Average results of the CMOD tests.

	f_t [MPa]	f_{LOP} [MPa]	$f_{R,1} * 0.27$ [MPa]	$f_{R,3} * 0.27$ [MPa]	$f_{R,3} * 0.27 /$ $f_{R,1} * 0.27$	Class
CMOD-E-I α -O1	5.29	3.52	4.06	4.59	1.13	c-e
CMOD-E-I α -O2	4.99	3.14	3.87	4.83	1.25	d-e
CMOD-D-I α -O1	7.32	4.03	5.03	6.92	1.39	d-e
CMOD-D-I α -O2	7.56	4.41	5.48	7.27	1.33	d-e
CMOD-D-I α -O3	7.76	3.92	4.99	7.27	1.46	e
CMOD-D-I β -O3	8.17	4.46	5.49	7.92	1.44	e

When comparing specimens sawn from different objects printed at the same 3D printing facility, the differences in maximum flexural strength are not substantial. As can be observed in Fig. 6, the relative difference in strength of specimens from the first and second objects printed is 5.6% (Eindhoven) and 3.3% (Delft), and 5.9% (Delft) for specimens from the first and third object printed. Also, the notch orientation (and associated specimen orientation during testing) did not significantly influence the failure response. The significant differences in the flexural strength of the specimens printed in Eindhoven and Delft may be associated with differences in the internal material structure, which will be analyzed in more detail in the section below.

4.3 Apparent Density and Air Void Content

After the CMOD experiments were performed, the apparent density of the specimens was measured. The results summarized in Fig. 6 show that the average apparent densities, plotted by the light (Eindhoven) and dark (Delft) grey bars, did not change significantly during the printing sessions. Further, the specimens manufactured in Delft have an average density that is approximately 7% higher than those manufactured in Eindhoven, which explains their higher flexural strength indicated by the oblique hatched bars.

The cross-sectional images obtained from the μ CT-scan of the specimen indicate a significant variation in air void content within the layers, see Figs. 7 and 8. Moreover, the distribution of the air void sizes across the specimen height shows that the interfaces between printed layers show a local increase in air void size. For the Delft specimen the average air void content within the layers ranges from 6.7% to 8%, while for the Eindhoven specimen it ranges from 15.2 up to 19.7%. This explains why the density and flexural strength of the Delft specimens are higher than those of the Eindhoven specimens. Further, the layer interfaces of the Delft specimen shows to have a higher average air void content than within the layers, while the Eindhoven specimen show the opposite trend.

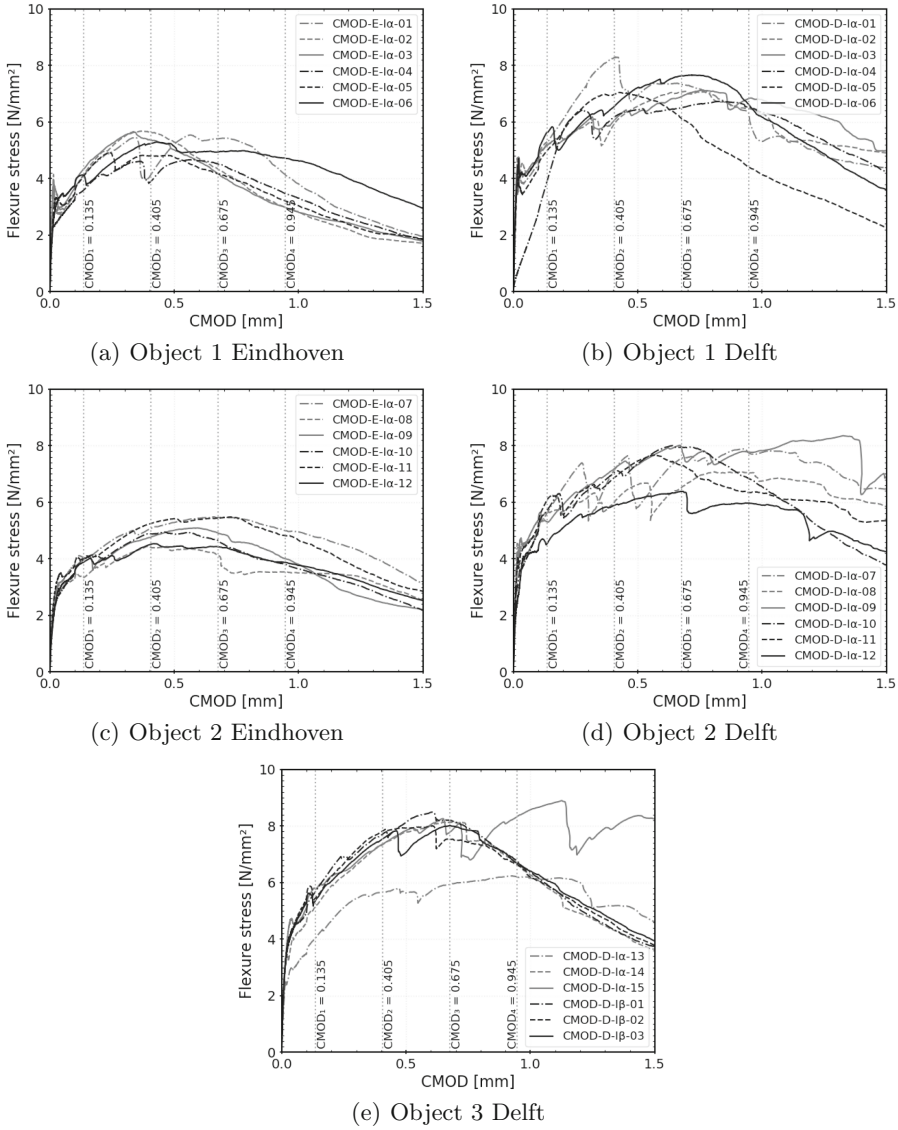


Fig. 5. Flexural stress versus CMOD of all specimens.

In addition, for both the Delft and Eindhoven specimens the void size within the layers is in the range of 0.01 to 0.016 pixel². However, for the Delft specimen the voids at the layer interface range from 0.016–0.031 pixel², which is larger than the range of 0.016 to 0.026 pixel² measured for the Eindhoven specimen. Hence, the layers interfaces of the objects printed in the Delft facility contain larger air voids than the layer interfaces of the objects printed in Eindhoven.

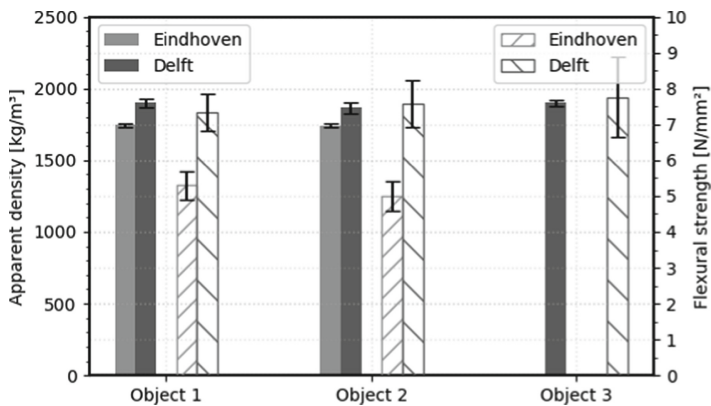


Fig. 6. Average apparent density (grey) and average flexural strength (hatched) of the specimens manufactured in Delft and Eindhoven.

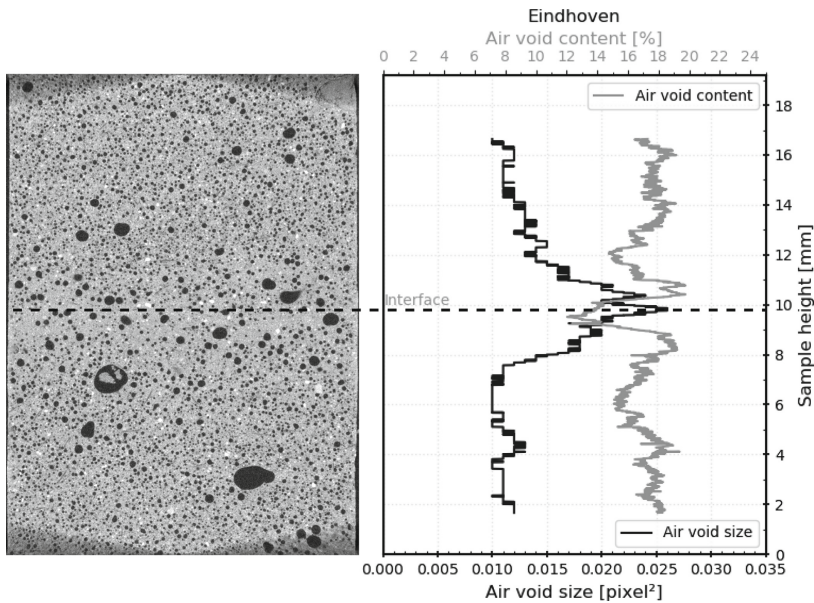


Fig. 7. Air void content and size across the height of a specimen printed in Eindhoven. The dashed line designates the interface between the printed layers.

Figure 9 shows an example of relatively large air voids found within the printed layers in a Delft specimen.

The differences in the properties observed for hardened specimens may originate from the mixing characteristics of the fresh concrete, such as the dissolution time from the VMA or superplasticizer, the fibre dispersion, and the entrapment

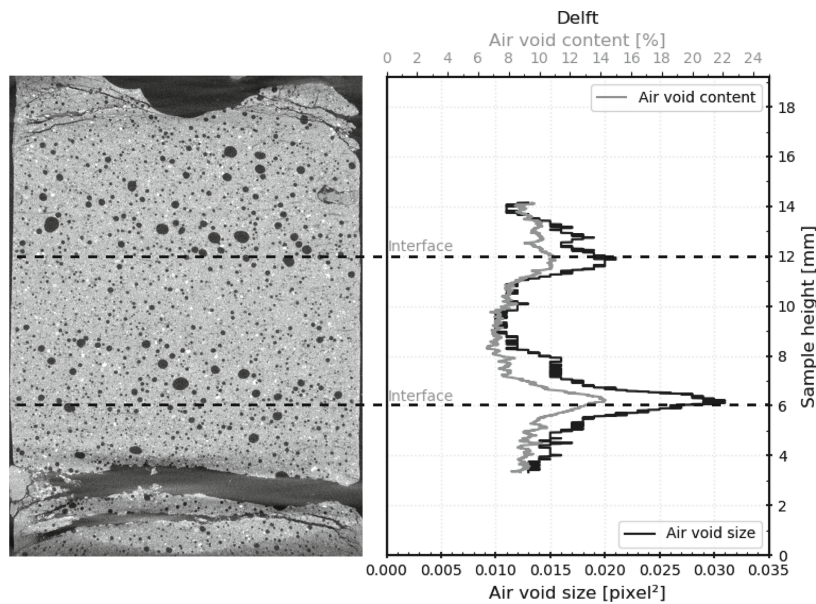


Fig. 8. Air void content and size across the height of a specimen printed in Delft. The dashed line designates the interface between the printed layers.

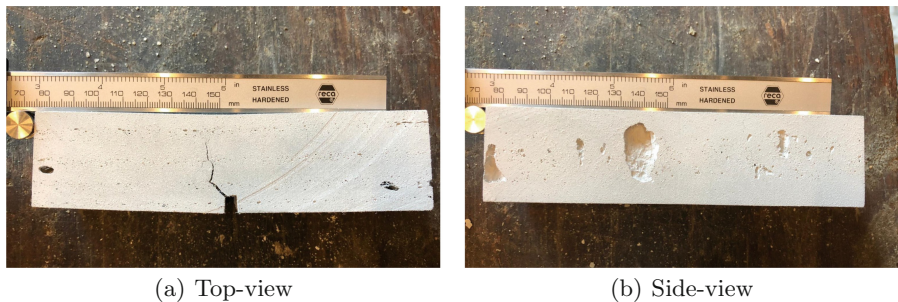


Fig. 9. Large air voids in specimen printed in Delft and tested in direction $I\alpha$.

of air during mixing. Previous work has indeed demonstrated how VMA can influence the total air void content of the cement paste [22]. Additionally, it is important to emphasize that the mixer in Eindhoven is significantly more powerful than the one in Delft, and that the mixing time in Eindhoven was adapted to reach the same visible consistency. Therefore, it may be reasonably expected that the mixing procedure has a strong effect on the total air void content of the printed material.

The relatively large air voids found in specimens from Delft could be explained by the pumping mechanism. The paddles, exemplified in Figs. 2(c)

and 2(d), rotate in order to collect the material from the reservoir and push it towards the rotor/stator. Due to the high viscosity of printable SHCCs, some air pockets might have been created during this stage. It is hypothesised that a coarse rotor/stator system (Delft) can transport these large air pockets as a whole, whereas a fine rotor/stator system (Eindhoven) might break these large air voids down into smaller voids. However, more research is needed to explore such differences in more detail.

5 Conclusions

- The mechanical and physical properties of the specimens manufactured in the 3D printing facilities in Delft and Eindhoven were significantly different. In order to reduce these differences, standardization of printing methods and full understanding of printing variables is of crucial importance.
- The mixing time and intensity have a strong influence on the quality of dough-like mixtures. Longer mixing times introduce entrapment of air voids in the fresh state, which causes a reduction in mechanical properties.
- Based on the collected data no significant differences were found in the mechanical results in relation to the temperature history of each object.
- The total air content found in specimens mixed and printed at different 3D printing facilities may vary significantly. This turns out to have a considerable effect on the mechanical properties in the hardened state.

Acknowledgements. This research was funded through the NWO Open Technology Program, project ‘High Performance 3D Concrete Printing’, grant number 17251.

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More Than Meets the Eye? Robotisation and Normativity in the Dutch Construction Industry

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Abstract. Construction robots are becoming more common in the Netherlands, but remain rarities in contexts aside from state-of-the-art factories owned by wealthy or technologically-orientated companies. In its current state, the construction industry would have to change significantly to make room for robots. To understand whether these changes are welcome or not, this paper presents qualitative, exploratory research concerning 10 stakeholders' perspectives of robotisation and construction robots in the Dutch construction industry.

Keywords: Robotisation · Stakeholders · Industry 4.0 · Construction industry · Ethics · Health and safety · Trade unions

1 Introduction

During one of the first interviews we conducted for this study, we asked a participant, who works at 3D-printing company, to define robotisation. Without hesitation, they stated 'that robot' then pointed towards a mechanical arm, standing in the corner of their lab. At the risk of over-interpreting their statement, their readiness to define 'robotisation' qua a physically present and operational robot highlights something worth discussing. Thanks to innovations in additive manufacturing, computer programming and industrial engineering, their company has created a mechanical replacement for human concrete workers, that never needs vacation time or suffers from backaches (Contant 2014). The robot manoeuvres on a linear track and funnels concrete from its arm to build 3D objects for construction purposes. Although it may outperform human workers, it must remain within a controlled, sheltered setting while it works.

If everything stays the same within the Dutch construction industry, this robot and others like it will likely remain rarities. To make room for them, many aspects of construction work need modification. Whether stakeholders see these changes as welcome remains largely unknown. Although substantial research has been conducted on robots' negative and positive impact on working conditions in other industries,

accounts that focus on construction are scarce. This holds true in countries aside from the Netherlands, but for this research paper we exclusively focus on the Dutch context. After providing a state-of-the-art literature review on construction robots in the Netherlands, this paper will present exploratory, qualitative work concerning stakeholders' perceptions of these technologies and robotisation. It will put forward the following claims:

1. The term 'robotisation' carries significant normative weight within the Dutch construction industry and represents a desirable or undesirable progression away from the status quo.
2. Many aspects of the Dutch construction industry require modification to accommodate robots
3. According to our participants, increased robot uptake will have multifarious positive and negative affects on the construction industry.

2 Literature Review

Construction robots are becoming more common in the Netherlands. In the past three years alone, two of the largest Dutch construction contractors, BAM and Bruil, opened their first robot-centred factories^{1,2}. Nowadays, many off-site manufacturing plants in the Netherlands also (partially) rely on robots, to produce components for construction purposes such as timber and welded steel. Several, small-scale but noteworthy start-ups have increased their robot uptake too³. Including MX3D who received significant media attention over the past two years, after they employed custom-built robots to complete a steel, pedestrian bridge ready for installation on Amsterdam's Oudezijds Achterburgwal canal (Buchanan and Gardner 2019). These robots almost exclusively operate behind closed doors, in contexts more akin to factories than construction sites. Like most other industrial robots, they were created to perform structured activities in enclosed spaces, built to accommodate them.

When compared to factory-floors, construction sites are hostile environments for robots. Every construction site changes from day to day, and has its own, unique environmental hazards, including heavy moving objects and varied geographical elevations. Also, human workers are unpredictable. Whereas one may prefer to carry loads under their left arm, another might move the same object by perching it on their right shoulder. It is (currently) impossible to account for every action workers might perform on construction sites, as human behaviour varies massively between individuals. Designing robots to safely operate in dynamic environments of this kind is challenging, as it is necessary to equip them with state-of-the-art software and hardware that allows them to process sensory data (Helm et al. 2014). For these reasons, it is unlikely that robots will appear en-masse on construction sites on short notice.

¹ <https://www.baminfra.nl/nieuws/primeur-weber-beamix-en-bam-infra-openen-3d-betonprintfaciliteit>.

² <https://www.bruil.nl/prefab-printing>.

³ For instance, RAMLAB, MX3D, Cybe, and Vertico.

Aside from the exceptions mentioned earlier, Dutch construction companies tend to avoid robots. It is difficult to find reliable numbers, but current figures suggest that only 3% of construction companies employ robots in some capacity. A percentage that stands well below the production sector's national average (29%) (de Leeuw 2019). Of course, companies cannot purchase new technologies unless they are available on the market. This issue has undoubtedly stalled uptake rates in the industry, as construction robots weren't available for purchase until recently. Even though vendors such as ABB, Kuka and Universal Robots are currently working to increase construction robots' availability, other factors would almost certainly dissuade construction firms from investing in robots. Among the 194000 currently active Dutch construction companies, 193000 (99%) employ less than 50 workers. And the majority of these companies are one-person operations (CBS Statline 2020a). Generally-speaking companies of this size lack the financial capital necessary to invest in robots, let alone the scientific know-how to adapt their production strategies around these technologies.

This isn't to say there's no demand for construction robots. On the contrary, the Dutch construction industry currently suffers from a severe lack of workers. While the demand for new homes, roads and civic buildings has risen over the past decade (Doodeman 2019), the number of available construction workers has decreased from 543000 in 2008 to 475000 in 2018 (CBS Statline 2020b). These decreasing numbers reflect that construction has become an unattractive profession for new workers.

When occupational hazards and health risks are taken into account, it is unsurprising that people prefer to look elsewhere for work. According to a report by Nederlands Centrum voor Beroepsziekten (NCvB) published in 2018, construction workers risk developing many occupational diseases over their careers. Indeed, construction is the 13th (out of 44) worst profession in this regard and ranks number 2 when it comes to conditions 'of posture and body movement' (NCvB 2019). Considering that other industries facing similar problems have started to turn to robots in recent years, it seems logical for construction to follow suit.

At this point, it worth returning to our participant's remark - which we cited at the beginning of this paper. In light of the information outlined above, does their robot and others like it represent robotisation? To answer this question it is necessary to define robotisation. Or more precisely, what this term means for the Dutch construction industry. By presenting research concerning relevant stakeholders' perspectives on construction robots and robotisation, this paper addresses this task.

3 Methods

The Collins English Dictionary defines robotisation as 'the introduction of robots to carry out industrial tasks'. Before setting out to gather insights on stakeholders' attitudes towards robotisation, we were aware that this term would likely carry significance beyond its dictionary definition. As robots remain largely absent from the Dutch construction industry but have the potential to meet demands that are currently unsatisfied, we expected that robotisation would signify change to some degree for our participants. Like other words with -ation suffixes, it implies an ongoing process. With this in mind, we chose to (preliminary) interpret robotisation as the movement towards

a state-of-affairs where robots are more present and operational in the Dutch construction industry. We anticipated that our participants would express their support or opposition towards this process. Or in ethical terms: employ normative language to talk about robotisation and construct robots in general. Overall, we aimed to answer the following research questions:

1. How do participants working in the Dutch construction industry define ‘robotisation’?
2. What normative connotations do they attach to this term?
3. What do stakeholders consider to be the advantages and disadvantages of robotisation?

We relied on convenience sampling to recruit participants, by approaching ten stakeholders we knew were active in the Dutch construction industry and knowledgeable of robotics. To ensure that our participants’ interests and perspectives were heterogeneous, we contacted stakeholders representing the following, distinct groups.

Academics

Number: four

Summary: All four, leading technological universities in the Netherlands have established research projects dedicated to construction robots over the past few years. Because they have expert knowledge of robotics and the Dutch construction industry at large, we arranged interviews with academics working on two of these projects. Among them were two full professors, one associate and one assistant professor.

3D Printing Experts

Number: two

Summary: At least in the Netherlands, construction robotics and 3D-printing go hand in hand. Most construction robots found in the Dutch context are effectively programmable, semi-autonomous 3D-printing machines that can move around three or more axes. As such, we chose to speak with stakeholders from this field who work with robots.

Trade Union Representatives

Number: four

Summary: Within the literature on robotisation, authors often suggest that increased uptake in industrial robots may displace or de-skill workers (Frey and Osborne 2017; Schwab 2017). As such, it was important for our research to gather insights from workers on robotisation. Due to time constraints, we couldn’t directly interview workers, so instead chose to speak with their trade union representatives, working for the two largest unions in The Netherlands. As these stakeholders are responsible for improving trade union members’ employment conditions, their opinions at least partially reflect workers’ concerns.

Due to the exploratory nature of the research, we employed a semi-structured format during the interviews. More specifically, we created a selection of open-ended questions beforehand to guide the interviews, but left time for participants to discuss other, relevant topics. Before we began, we briefed each participant about the nature of our research and asked them to sign an informed consent slip to show that they agreed

to take part in the study (which they did unanimously). After the interviews were completed, they were fully transcribed then manually coded to identify thematic similarity and differences (Braun and Clarke 2006; Charmaz 2014; Thomas 2006). To preserve our participants' privacy, we have omitted their names from this research paper and only refer to them according to their occupation, coupled with a numerical value (e.g. Trade Union Representative 1). All interviews were conducted in Dutch, but quotes in this paper have been translated into English. Before presenting our results, it is necessary to state that these findings are exploratory and represent an interpretation of our participants' responses.

4 Results

4.1 What is Robotisation? (According to Our Participants)

At the beginning of the sessions, we asked each participant to define robotisation. As it was our opening question, we expected largely descriptive responses from our participants. However, they almost unanimously provided accounts of robotisation that were value-laden. Before outlining these results though, we should make clear that our participants were aware of the nature of our research and knew that we were gathering insights on robotisation's normative significance. Hence, their responses were almost certainly influenced by this.

Most of our participants implied that robotisation substitutes human labor. They agreed that robots are programmable, autonomous machines that perform production tasks. Many suggested that robotisation would help ease labor shortages, by providing means to complete activities that were previously fulfilled by humans. However, their descriptions regularly veered into normative territory and served to justify or question the legitimacy of robotisation.

Around one third of our participants tailored their responses around robotisation's potential to invigorate the construction industry. Many highlighted that construction has historically trailed behind other industries in terms of productivity, because it suffers from some form of technological conservatism. Robotisation, they argued, would buck this trend and bring construction into the twenty-first century. As Academic 1 states:

"We do it [construction] in a very traditional way. We have been doing it the same for years. For example if you look studies on productivity and so on, you see that construction is lagging behind. There is hardly any increase in productivity compared to other industries that are fully automated or robotized".

Aside from improving productivity, Academic 1 stated that robotisation would bolster sustainability - a relatively new concern within the production sector at large (van de Poel 2018). Academic 2 shared similar thoughts, but went a step further by suggesting that we, as a society, cannot afford to let construction stagnate, as productions demands are simply too high to ignore. The idea that construction needs to catch up with other industries, for its own and society's sake, was mentioned many times during this phase of the interviews. Academic 2 also mentioned the social obligation to work more efficiently, not to make more money, but to allow society to

spend the saved money on more important things than construction, such as education, elderly care or climate. Indeed, participants seemed to tie robotisation to beneficial growth in general.

Of course, what's good for society - or in this case the construction industry- isn't always good for the individual. The majority of participants implied that robotisation will disrupt traditional working conditions. More specifically, they suggested that skills that were once valued in the construction industry, may become antiquated due to robotisation. Workers who rely on traditional methods to complete tasks will experience the brunt of this change. None of our participants unequivocally stated that robotisation would increase unemployment, but they did suggest that some workers will face de-skilling. Trade Union Representative 1 was clear about this point:

"Robotisation also has consequences for the content of work. Sometimes it also has the effect that people feel that their function is being eroded, as it were, the traditional is being taken over by the robots".

It is worth highlighting that both Trade Union Representative 1 and 2 explicitly mentioned that de-skilling may cause emotional or psychological distress for workers. They implied that robotisation may take something away from workers and create holes that were once filled by traditional labor. Traditional work, they suggest, has value beyond productivity for workers. Trade Union Representative 1 continued by giving an example involving bricklaying robots. They suggested that there's no need for experienced, human bricklayers to employ their expert skills when these machines are present. As they state, human bricklayers 'only have to clean up the mess that the robot leaves behind'. Rather than outright opposing robotisation for these reasons, they argue that these problems need to be addressed to ensure that workers can still access meaningful work in construction.

After looking over our participant's responses, we noticed that they tended to portray robotisation as something that creates new opportunities for the construction industry while limiting others. When viewed collectively, their responses implied that there's a tension between old and new means of production, as reflected by their regular references to 'traditional' manners of work. Whereas some saw this traditionalism as problematic, other recognised that it currently gives meaning to workers employed in the industry. Overall, their responses demonstrated that 'robotisation' represents a desirable or undesirable progression away from the status-quo.

4.2 Advantages and Disadvantages/Opportunities and Limitations

After the first stage of the interviews, we continued by asking our participant's more in-depth questions concerning robotisation's significance for the construction industry. To ensure that their responses were relatively structured and prompt them to express their opinions on this subject matter, we framed these questions around the themes of "the advantages and disadvantages of robotisation". For instance, by asking them "Could you tell me about the benefits of robotisation, generally-speaking?" followed (or preceded) by questions such as "Do you also see any disadvantages?".

The majority of participants provided responses that followed these themes, for instance by highlighting that robots are expensive (disadvantages), but nonetheless

lower production costs once deployed (advantages). After assessing our interview transcripts, we discovered that two other themes were identifiable, which we labeled as “the limitations and opportunities of robotisation”. Our participants frequently expressed that the construction industry in the Netherlands has its limitations in regards to robots and cannot accommodate them in its current state. As Academic 1 stated:

“Yes, you see, construction is traditionally also a bit more conservative. [Profit] has to be achieved on projects, so you cannot innovate very easily if you always have to deliver a project. If you look at telephones or cars, they are completely engineered and optimised, and from there tens, millions are made of them, and with buildings and civil works that is of course more difficult”.

Unlike mass-produced objects such as telephones or cars, Academic 1 suggests, construction projects are unique. It is difficult to develop a one-size-fits-all approach to construction, as industry actors must deliver products (buildings, civic works, etc.) that are highly differentiated from one another. According to Academic 1, the unique nature of construction projects hinders innovation in the field. Because they are responsible for creating products that don’t lend themselves to mass-production, industry actors would risk losing out financially (or otherwise) if they were to innovate their workflows. It is worth highlighting here, that Academic 1 refers to construction as ‘traditionally a bit more conservative’ and ties this quality to the industry’s general approach towards production. For them, it seems, ‘traditional’ and ‘conservative’ mindsets are present in the industry, because contemporary material and economic conditions limit the availability of alternative means of production.

In contrast, several participants expressed that robotisation opens the door for new opportunities in construction, that could bypass or address the industry’s limitations. For instance, Academic 4 highlights that contemporary construction processes are usually developed to create specific products, on a largely project by project basis. When industry actors are tasked with building a bridge, for instance, they design their production processes around this product. After the project is completed, its tailor-made production processes effectively become redundant, as they were specifically designed to fulfil one purpose, in this case, the creation of one particular bridge. Rather than continuing to follow this strategy, Academic 4 suggests that processes should take centre stage and be optimised via robotisation. As they state:

“We do not optimise the process, we are actually starting a new process again. [We] still place the viaduct [the product] at the centre of our industry and then start designing something to make that viaduct. We should start designing our processes”.

For Academic 2, the construction industry should take into account available resources, for instance robots, then create production processes that harness these technologies’ strengths. By recognising what robots can and cannot do, it becomes possible to design production processes around them. Rather than building twenty different bridges by implementing twenty different production processes, Academic 2 suggests that industry actors should standardise their approaches to some degree by creating repeatable strategies that utilise robots and other technologies (relevant) capabilities. For Academic 2 at least, robots provide the industry with an opportunity to move away from its focus on products over processes.

Our participants mentioned many other advantages, disadvantages, limitations and opportunities they associate with robotisation during our interviews. With this in mind, we clustered their remarks into 14 additional sub-themes listed below, which represent recurrent or significant topics that were discussed during the interviews.

4.3 Advantages

Number: three

Summary: All participants expressed their support for robots at some point during our interviews, by referencing ways these technologies could improve various socio-economic conditions associated with the Dutch construction industry. We have clustered together comments of this kind as “Advantages”.

Health and Safety

Almost every participant mentioned that robots would improve health and safety to some degree in the industry, by performing dangerous tasks previously fulfilled by humans. Additionally, several participants highlighted that workers often develop chronic health condition from years of manual labor. If robots were employed to carry out strenuous tasks that contribute to these health problems, workers would benefit.

Productivity and Precision

According to many of our participants, robots stand to improve productivity in the construction industry, as they can produce resources faster, more effectively and on a larger scale than humans. Also, robots are considerably more precise than humans and the products they create are cut, welded or sawed with mathematical accuracy. As a side-note, several participants also mentioned that robots can create unique products, including seamless 3D-printed objects, thanks to their heightened precision and ability to operate uninterrupted over long time-periods, thus addressing the demand for ‘mass-customised’ objects.

Costs

Many of our participants claimed that employing robots to perform construction tasks could lower production costs. They mainly justified this claim by referencing how robots improve productivity, which in turn would lower the financial cost of producing construction resources. For instance, Academic 3 references how other industries have lowered costs this way:

“Generally in the manufacturing industry, the costs of the products have of course gone down enormously. The more you control automatically, the more you can produce for very little”.

4.4 Disadvantages

Number: five

Summary: All participants made clear that robots may create new or contribute to pre-existing problems associated with the Dutch construction industry once deployed. We have clustered comments of this kind together as “Disadvantages”.

Productivity

Whereas most participants mentioned that productivity would increase due to robots, 3D Printing Expert 1 highlighted that this isn't necessarily the case. More specifically, they stated that employing 3D-printing technology to mass-produce products is more time-consuming than relying on traditional construction methods at the moment. Overly relying on these methods then, could lead to lower production rates for the industry.

Social Acceptability

Because they are novel, largely untested technologies, many participants highlighted that people may distrust robots. It is still unclear how (or whether) robots actually add value to working environments. Indeed, workers may treat them as objects that hinder their ability to work and have very little incentive to interact with them. Additionally, Trade Union Representative 3 stated that contractors have historically shown discontent whenever they were forced to implement new technologies they view as unnecessary.

Unemployment, Adaptability and Meaningfulness of Work

As stated earlier, none of our participants suggested that robots will displace workers from their jobs. However, several did suggest that workers may fear this outcome nonetheless and therefore oppose increased robot uptake. Even if workers aren't concerned about this, some may have trouble adapting to robots, especially older people who have spent their entire careers relying on traditional construction methods. Also the risk was mentioned that robots could make the work of human workers less valuable and less meaningful, possibly leading to reduced satisfaction and sense of contributing.

Collective Labour Agreements

Trade Union Representatives 3 highlighted that increased robot uptake could jeopardise their unions' ability to create collective labour agreements on construction workers behalf. Like other trade unions, they negotiate with employers to improve employment conditions for workers. Robots are machines, and do not need representation by a union, thus reducing the reason for the existence of unions. Furthermore, companies that produce, own or operate robots aren't usually considered construction firms or indeed employ construction workers - thus they are not represented or impacted by trade unions' decisions.

Disruptive Wealthy Actors

Several participants expressed their concern that wealthy, technologically-focussed companies, such as Google, may see an opportunity in the future to disrupt the construction industry by financing 'brands' that employ state-of-the-art robots for construction purposes. As smaller firms almost certainly wouldn't have the means to compete with multi-national companies like Google, they may face difficult times.

4.5 Opportunities

Number: three

Summary: Many participants discussed how robots could provide actors with opportunities to overcome or address contemporary issues associated with the Dutch construction industry. These comments were similar to those clustered as “advantages”, but focused on how actors could bypass or navigate around problematic socio-economic conditions by employing robots - rather than how robots could outright improve conditions in the industry. We have clustered comments of this kind together as “Opportunities”.

Public Image and Appeal

Several participants suggested that increased robot uptake would improve the construction industry’s public image. For one, it would demonstrate to external actors that the industry was attempting to improve its production methods in accordance with modern technological developments. Additionally, it could make the industry more attractive to new workers, especially young people who may see robots as appealing.

Replicating Successes from Other Industries

Throughout our interviews, many participants claimed that construction ‘lags behind’ other manufacturing industries in regards to innovation. Several suggested that construction should emulate other industries to increase innovation, for instance, by borrowing methods involving robots from other fields that have proven successful. Rather than starting from scratch, this would allow construction to learn from other industries’ successes (and mistakes).

Adoption of Better Business and Production Strategies

Many participants spoke extensively about how they viewed the construction industry as ‘traditional’ or ‘conservative’. They tended to use these words to describe business and production strategies they saw as outdated or ineffective. Several made clear that increased robot uptake could change this situation, by allowing industry actors to experiment with different, potentially more advantageous business or production strategies.

4.6 Limitations

Number: three

Summary: All participants highlighted that the Dutch construction industry is currently ill-suited to accommodate robots, in some way or another. Or conversely, that contemporary robots are ill-suited to operate within the industry. We have clustered remarks of this kind together as “Limitations”.

Investment Costs

Many participants mentioned that robots are prohibitively expensive for most actors working in the Dutch construction industry. They explained that most companies don’t have the financial capabilities to justify investing in robots. Additionally, some participants made clear that construction companies in the Netherlands often work with tight-budgets and must deliver unique, large-scale products under time constraints.

Thus, it is unlikely they would invest in expensive robots, when they could instead simply rely on tried-and-tested traditional methods which have consistently proven successful in the past. It is worth noting here, that many participants expressed that it is difficult to innovate in the construction industry for these reasons.

Working Conditions

Several participants explained that robots work best in structured, standardised environments that bear little resemblance to traditional construction sites. As each construction site is unique, robots would need to be highly flexible to operate within them. Several participants mentioned that construction ‘lags behind’ other industries for this reason, as actors must create products (building, bridges, etc.) in environments that don’t lend themselves to automatised processes.

Sequential Work Patterns

As construction work involves many different tasks, that eventually lead to the completion of one large product - namely a building or series of buildings - its workflows are highly sequential. Several participants expressed that robots are ill-suited for sequential work patterns, as they can only perform one set task, for instance welding steel or cutting timber. Whereas a single human worker can cut, carry and install timber elements (“from foundation to roof”), robots can only complete one of these tasks. Even when they do take part in sequential work, robots can only complete singular tasks, leaving human workers to perform everything else. Especially in renovations of existing building stock, robots would have a hard time, since they would be confronted with many unforeseen surprises that require human improvisation and ingenuity.

5 Conclusion

Innovation in any industry rarely, if ever unfolds without a hitch. Whenever new technologies are introduced to pre-existing contexts, ‘it is possible, and even likely that there will be unanticipated social consequences’ (van de Poel 2013). Our participants’ attitudes towards construction robots reflect this statement. Construction robots, for them, have the potential to ease many issues related to construction, while helping to improve productivity, sustainability, safety and working conditions (etc.) in the industry. Nonetheless, these improvements aren’t cost-free and robots may contribute or create new problems once deployed according to our participants.

Furthermore, they were clear that the industry itself - or at least certain aspects of it - could or would benefit from higher robot deployment rates, but will also stall this process for various reasons. The main hurdles here include the industry’s focus on creating unique, complex products in physically demanding work environments and reliance on small-scale companies. Many participants highlighted that these ‘traditional’ or ‘conservative’ approaches towards production has significant pitfalls that could be addressed by robots, but will also slow down uptake rates because they are the norm within the industry. With this in mind, it is worth asking: does the construction industry actually have sufficient space for robots? In its current state, probably not. Robots are still rarities and our participants frequently suggested that many things need to change to accommodate them.

It is perhaps more constructive then, to focus on how the industry would need to adapt around robots, rather than centring discussions around how robots will change the industry. Many of our participants remarks make more sense from this perspective, as they frequently discussed socio-economic factors that require attention before robots could be deployed in significant numbers. To be clear, if robots were to become present and operational in more construction contexts, it would be safe to assume that the industry had already undergone substantial changes. Our participants definitions of 'robotisation' aligns with this theme. According to our interpretation, many of them suggested that 'robotisation' signifies a movement away from 'traditional' or 'conservative' production methods - which, for better or for worse, requires change to gain momentum.

As our research was exploratory and only involved ten participants, its result are limited. Nonetheless, we have shown that 'robotisation' means substantially more than its dictionary definition implies and carries significant normative connotations for our participants. Additionally, this contribution has outlined several, distinct ways robots may positively or negatively impact the construction industry - according to our participants. Due to the limited nature of this research, we did not recruit construction workers or contractors as participants. Considering that they will be affected by the (potential) changes outlined above, we highly recommend that further research in this area takes into account their perspectives.

Acknowledgement. The authors are grateful that the interviewees made their valuable time available for this study. The author Tom Coggins received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 788321, as part of the project ValueChang

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Influence of Processing Parameters on the Layer Geometry in 3D Concrete Printing: Experiments and Modelling

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Abstract. This paper presents the numerical simulation results of a computational fluid dynamics (CFD) model that describes the layer shape in extrusion-based 3D Concrete Printing (3DCP). The simulation outcome is validated through an experimental program in which we investigated the influence of 3DCP processing parameters on the geometry of a single layer. Specifically, a set of single layers were printed using a Ø25 mm nozzle mounted on an 6-axis industrial robotic arm travelling at different speeds and with different layer heights. A fresh concrete – comprising CEM I 52,5 R - SR 5 (EA), limestone filler, fine sand, water, and admixtures (i.e. viscosity modifying agent, high-range water-reducing admixtures and a hydration retarder) – was pumped and extruded at a fixed volumetric rate. Once hardened, the extruded layers were sliced to examine the resulting cross-sections. Specifically, the cross-sections' geometry were obtained by a custom image processing algorithm. Next, the extrusion flow was modelled with a CFD simulation using the software *FLOW-3D*[®]. The constitutive behavior of fresh concrete was modelled as a Bingham fluid, while the volume-of-fluid method was used to predict the free surface of the concrete and, thus, the layer geometry. The numerical results agree qualitatively with the experimental observations, enabling us to identify two non-dimensional 3DCP processing parameters that influence the overall cross-sectional shapes: 1) the geometric ratio between layer height and nozzle diameter, and 2) the ratio between the nozzle velocity and the extrusion volumetric flux. These findings – when complemented with a model describing the overall deformation of stacked layers – serve as the basis for correlating material rheological properties to 3DCP process parameters, promoting a better link between design and fabrication in a 3DCP context.

Keywords: 3D concrete printing · Computational fluid dynamics · Extrusion flow · Layer geometry · Numerical modelling

1 Introduction

Automation of construction techniques is expected to considerably shorten fabrication time, reduce the need of physically demanding labor, increase safety on construction site, and lessen the overall construction costs. In terms of application, one of the main digital fabrication technology is extrusion-based 3D Concrete Printing (3DCP). 3DCP consists in extruding a fresh cementitious material along a computer-generated toolpath to build a concrete structure layer by layer [1]. The motion of the extrusion nozzle is generally controlled by a robotic arm or a gantry system. 3DCP solutions can be directly implemented on construction sites, to print an entire building, or off-site, to manufacture assembly components. 3DCP circumvents the need of formwork and implies different design rules as compared to conventional construction, which allows novel architectural concepts without compromising production costs and flexibility.

Some of the current 3DCP challenges include the improvement of the surface finish quality, the geometrical conformity, and the inclusion of reinforcements. Apart from research and development in robotics and machine design, one of the key aspect for a successful deployment of 3DCP is the formulation of printable concrete mixtures. Concrete materials used in 3DCP have different requirements from classical concretes used in conventional applications. In particular, two of the requirements are contradictory: the 3D-printed concrete must be *flowable* (easy to flow) inside the pumping system, and *buildable* (capable of carrying a load without deformation) just after extrusion – these properties primarily depend on the open time of the material [2]. The concrete should undergo enough hydration to carry the load of subsequent layers. However, it should not harden before the printing of the next layer to enable proper interfacial adherence without the formation of cold joints. Therefore, the suitability of a cementitious material depends on not only its time-dependent rheological properties, but also the printing parameters and the component size (number of layers, vertical build-up rate, etc.). Relations between printing parameters, rheological requirements, and failure modes (plastic collapse, elastic bucking, cold joints, etc.) are discussed in [3, 4].

Numerical simulations have proven to be useful for improving the control of cementitious flows in various construction processes. Computational fluid dynamics (CFD) simulations have successfully been used to predict the flow of fresh concrete around reinforcements [5], concrete casting [6], or flow-related aggregate segregation in self-consolidating concrete [7, 8]. A review of the main computational approach to model the flow of cementitious materials can be found in [9]. CFD models were recently developed to simulate layer deposition in 3DCP [10]. Similar numerical models have also been used to simulate extrusion additive manufacturing of plastics [11–14].

In this paper, the deposition flow in 3DCP is simulated with CFD to predict the influence of printing parameters on the shape of the extruded layer. The numerical model uses a visco-plastic constitutive law. The material properties of a cement mortar used in 3DCP is characterized by rotational rheometry. In addition, 3DCP experiments with the cement mortar were carried out to validate the numerical model predictions.

2 Materials and Methods

2.1 Materials

The cement-based mortar used in the 3DCP experiments comprises a binder system with CEM I 52,5 R-SR 5 (EA) white cement, limestone filler, fine sand (maximum particle size 0.5 mm), water, and admixtures (a viscosity modifying agent, a high-range water-reducing agent and a hydration retarder). The mortar was prepared with an Eirich Intensive Mixer Type R08W (Capacity 75 l/120 kg). The binder system was mixed for 7 min, and the water was progressively added while mixing for the first 2 min. The hydration retarder admixture enhances the open time of the mortar, providing sufficient time for preparation, printing and cleaning of the 3DCP setup.

2.2 Rheological Characterization

The rheology of the fresh mortar was characterized by rotational rheometry, using an Anton Paar rheometer MCR 502. Fresh concrete is a well-known example of viscoplastic fluids exhibiting yielding behavior and there exist different methods to characterize the yield stress of concrete. In addition, the material has different yield stress values for the initiation and cessation of flow.

In 3DCP, the flow goes from a flowing state (during extrusion) to a cessation of flow (after deposition). Thus, the flow curve of the mortar was measured with a ramp-down controlled shear rate test. The rheometric test was performed in a vane-in-cup configuration with a 6-blade vane stirrer measuring device to avoid wall slippage. The equivalent annular gap of the geometry was 3.46 mm. In order to replicate the printing process, the rheometric measurements were done 30 min after the preparation of the mortar.

At the beginning of the test, the sample was homogenized by pre-shearing at 10 s^{-1} during 30 s. Then, the shear rate was continuously increased from 10 s^{-1} to 60 s^{-1} , with a constant shear rate acceleration of 0.5 s^{-2} . During that phase, the material undergoes extensive shear deformations that destroys reversible network structuration. Those large shear deformations are similar to those experienced during pumping in 3DCP. Afterwards, the shear rate was ramped down to measure the flow curve. A first measurement interval comprised 21 measurement points, evenly distributed between 60 s^{-1} and 10 s^{-1} , with a measurement time of 5 s per point. Next, a second measurement interval between 7.5 s^{-1} and 0.2 s^{-1} included 10 measurement points logarithmically distributed to provide more data points in the low shear rate regime. Moreover, the measurement time of these points was also increased logarithmically, i.e. from 5 s (at 7.5 s^{-1}) to 40 s (at 0.2 s^{-1}), so that the fluid was subjected to enough strain during the measurement time.

The measured flow curve of the mortar is shown in Fig. 1. A good fit of the experimental data is obtained by linear regression, with the curve $\tau = 7.5 [\text{Pa}\cdot\text{s}] \dot{\gamma} + 630 [\text{Pa}]$. When we neglect the data points below 1 s^{-1} , the coefficient of determination of the regression is $R^2 = 0.999$. Hence, the constitutive behavior of the mortar was modelled by the Bingham law. The yield stress corresponds to the vertical intercept of the linear regression and the slope of the line gives the plastic viscosity.

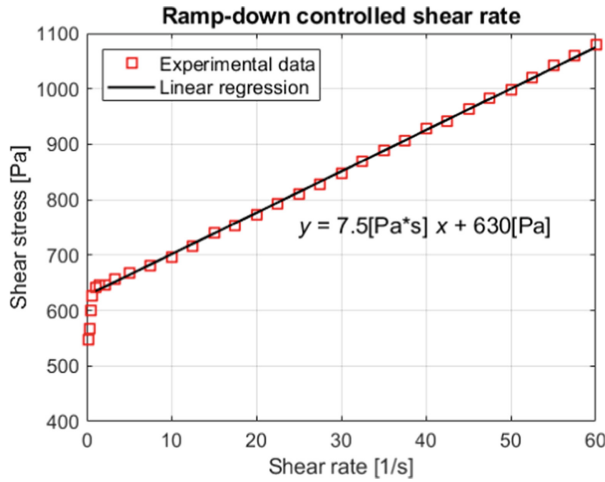


Fig. 1. Flow curve of the mortar measured by rotational rheometry.

2.3 3D Printing Experiments

The 3DCP experiments were carried out at the High-Tech Concrete Lab at the Danish Technological Institute. The 3D printing apparatus comprises a 6-axis industrial robot (FANUC R-2000iC/165F) and a progressive cavity pump (NETZSCH); see Fig. 2. The fresh mortar initially placed in a hopper is pumped into a rubber hose ($\varnothing 32$ mm, 3.0 m long). The other extremity of the hose is connected to a custom designed extrusion nozzle, whose position is controlled by the robot arm.

The experiments consisted in printing straight segments of length 50 cm on a planar build surface, for different values of the nozzle height (i.e. the distance from the nozzle tip to the build plate) and the printing speed (i.e. the travel speed of the nozzle). A circular extrusion nozzle with diameter $D = 25$ mm was used in all the experiments. Six segments were printed for two values of the nozzle height, $H = 12.5$ mm and 17.5 mm, and three printing speeds, namely $V = 30$ mm/s, 40 mm/s and 50 mm/s.

Before the printing experiments, the pump dial was set to deliver a volumetric flow rate of $19.6 \text{ cm}^3/\text{s}$, thereby a nominal extrusion volumetric flux of 40 mm/s. This flow rate was kept unchanged during the printing experiments. However, the effective extrusion volumetric flux U was found to vary during the print. By virtue of volume conservation, the extrusion flow rate, i.e. $V = \pi D^2 U / 4$, must equal the printing flow rate, i.e. $A \times V$, where A is the cross-sectional area of the printed segment. Therefore, the effective extrusion volumetric flux can be deduced from the relation:

$$U = \frac{4AV}{\pi D^2}. \quad (1)$$

After the mortar hardened, each printed segment was sliced through 4 cross-sectional planes. Scanned images of all cross-sections were post-processed using a Matlab[®] script that converts RGB bitmap images into polygonal contours. First, the

image processing script uses spatial filtering and image thresholding to detect a polygonal contour of the cross-sections. Then, the surface roughness of the contours is smoothed by downscaling the number of vertices and taking the convex hull of the polygon. The post-processing script also rotates and re-centers the polygonal contours of the cross-sections. Moreover, the script returns the cross-sectional area, the maximum layer width, and the median layer height (the layer height in the median plane) of the cross-sectional cuts. The effective extrusion volumetric flux of each segment was determined from the median area of its 4 cross-sectional cuts using Eq. (1). A summary of the processing parameters for each of the printed segment is listed in Table 1.

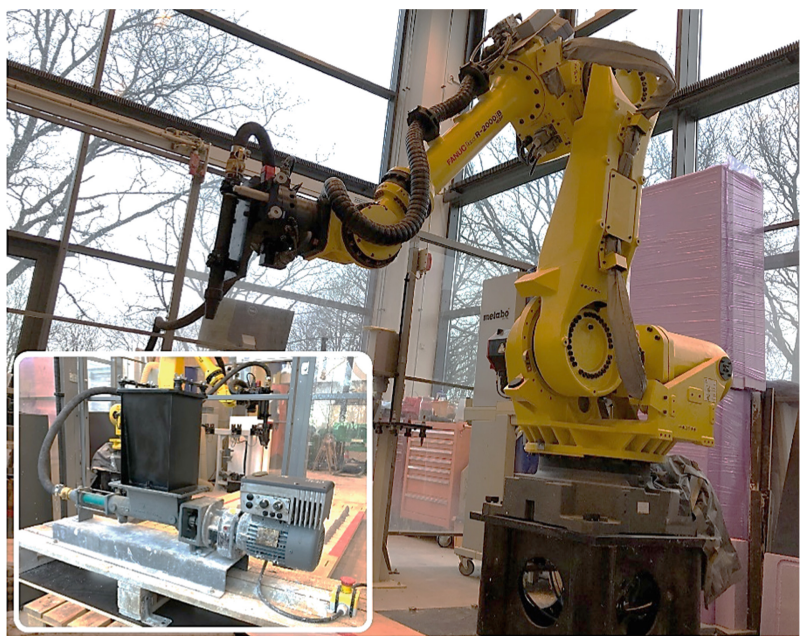


Fig. 2. Robotic arm and extrusion nozzle used for 3DCP. Hopper and pump are shown in the lower left frame.

Table 1. Process parameters of the printing experiments and simulations.

Process parameters	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Nozzle diameter, D [mm]	25	25	25	25	25	25
Nozzle height, H [mm]	12.5	12.5	12.5	17.5	17.5	17.5
Printing speed, V [mm/s]	30	40	50	30	40	50
Extrusion volumetric flux, U [mm/s]	33.6	31.6	33.4	26.7	46.1	36.9
Geometrical aspect ratio, H/D [-]	0.5	0.5	0.5	0.7	0.7	0.7
Speed ratio, V/U [-]	0.89	1.27	1.50	1.12	0.87	1.36

3 Numerical Model

3.1 Mathematical Model

In this study, the mortar is assumed incompressible, thereby it has a constant density ρ . This assumption imposes a divergence-free constrain on the velocity vector field $\mathbf{u}$ of the flow (continuity equation), i.e.:

$$\nabla \cdot \mathbf{u} = 0. \quad (2)$$

The dynamics of the flow is governed by the momentum conservation equation:

$$\rho \left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\partial p + \nabla \cdot \boldsymbol{\sigma}, \quad (3)$$

where p is the isostatic pressure and $\boldsymbol{\sigma}$ is the material's deviatoric stress tensor. The isostatic pressure results from the continuity equation, Eq. (2), whereas the deviatoric stress tensor is determined from the constitutive model of the material. Here, the Bingham law is formulated as a generalized Newtonian fluid model:

$$\boldsymbol{\sigma} = 2\eta_{\text{app}}(\dot{\gamma})\mathbf{D}, \quad (4)$$

where

$$\mathbf{D} = \frac{1}{2} (\nabla \mathbf{u} + \nabla \mathbf{u}^T) \quad (5)$$

is the strain rate tensor and $\eta_{\text{app}}(\dot{\gamma})$ is the apparent viscosity function of the mortar, which depends on the strain rate magnitude, i.e.:

$$\dot{\gamma} = \sqrt{2\text{tr}(\mathbf{D}^2)}. \quad (6)$$

The apparent viscosity of the Bingham fluid is given by a bi-linear viscous model:

$$\eta_{\text{app}}(\dot{\gamma}) = \begin{cases} \eta_{\text{max}} & \text{if } \dot{\gamma} < \dot{\gamma}_C \\ \frac{\tau_Y}{\dot{\gamma}} + \eta_P & \text{if } \dot{\gamma} \geq \dot{\gamma}_C \end{cases} \quad (7)$$

where τ_Y is the yield stress, η_P the plastic viscosity, and $\dot{\gamma}_C$ the critical shear rate.

When $\dot{\gamma} \geq \dot{\gamma}_C$, the material is considered *yielded*, and the shear rate is proportional to the excess of stress above the yield stress. On the other hand, the material is considered *unyielded* when $\dot{\gamma} < \dot{\gamma}_C$; however, unyielded material is assigned a finite viscosity value, $\eta_{\text{max}} = \tau_Y / \dot{\gamma}_C + \eta_P$, instead of a theoretical infinite viscosity of a perfect rigid body. Thus, $\dot{\gamma}_C$ is a regularization parameter that determines the maximum cutoff value of the apparent viscosity, which circumvents numerical singularity. For a large enough η_{max} (thereby a small $\dot{\gamma}_C$), the flow of unyielded material becomes unnoticeable, as it is very slow, and the bi-linear viscous model approaches the ideal Bingham law.

In this work, we chose a regularization critical shear rate $\dot{\gamma}_C = 0.01 \text{ s}^{-1}$, resulting in a maximum viscosity of the unyielded material that is roughly 100 times larger than the yield stress. Table 2 lists the material parameters used in the numerical simulations.

Table 2. Material parameters used in the simulations.

Material parameters	Values
Density, ρ [kg/m ³]	2100
Yield stress, τ_Y [Pa]	630
Plastic viscosity, η_P [Pa·s]	7.5
Critical shear rate, $\dot{\gamma}_C$ [s ⁻¹]	0.01
Maximum apparent viscosity, $\eta_{\max}$ [Pa·s]	63008

3.2 Simulation Framework

The numerical simulations of the layer deposition were carried out with the CFD software *FLOW-3D*[®]. The simulations focused on predicting the free surface of extruded mortar along a straight line. Thus, the simulation domain comprises the build volume of the virtual printed – but it does not include the pumping system and the pipe flow. The computational domain is a box with dimensions set at (350 × 80 × 50) mm. The simulation comprises two solid components: the build plate, at the bottom of the computational domain, and a moving cylindrical extrusion nozzle. The nozzle is positioned at the constant distance H above the build plate and moves horizontally with a constant speed, V , along a 300 mm rectilinear trajectory. The cylindrical nozzle has the inner diameter D and a wall thickness of 2.0 mm.

The computational domain volume is meshed with Cartesian grid planes. The governing equations of the flow, Eqs. (2) and (3), are discretized on staggered control volumes, with the finite volume methods. The full or partial blockage of grid cells due to the presence of the solid components is incorporated into the discretized governing equations with the immersed boundary method. As such, this approach does not require a body fitted mesh. The region where the mortar is printed has a uniform grid size of 1.0 mm. Note that, to reduce the total number of discrete variables, the upper region of the domain (where the nozzle travels but no mortar is extruded) has a coarser resolution with a vertical grid spacing of 2.5 mm. Also, only half of the domain is simulated, due to symmetry. In addition, the mortar adheres to the nozzle wall and the build plate, thus, the no-slip boundary condition was applied. An inlet boundary condition with the uniform velocity U is applied at the intersection of the extrusion nozzle with the last vertical grid plane. Other boundaries of the domain are continuative boundary conditions that allow fluids to exit the domain.

The free surface of the mortar is tracked with the volume-of-fluid method, using a geometrical interface reconstruction and a Lagrangian advection scheme. The mortar flow is solved with a single-phase solver, meaning that the flow of air in the “empty” grid cells is neglected. A decoupled pressure-velocity solver is used. The time step size is automatically adjusted by the numerical solver, according to numerical convergence.

4 Results

The CFD simulations provide details of the layer deposition flow. Figure 3 depicts snapshots of the mortar free surface outside the extrusion nozzle for different printing parameters. In the case of a low nozzle height x and a low speed ratio (Case 1 – Fig. 3a), the extruded material pushes the flow sideways and in front of the nozzle. This flow regime produces a large pressure on the substrate, which jeopardizes stability in multi-layer prints. The amount of mortar flowing on the sides and in front of the nozzle decreases when increasing the geometrical aspect ratio, H/D (Case 5 – Fig. 3b), and/or the speed ratio, V/U (Case 6 – Fig. 3c). In the latter case, the extruded material rolls on the substrate, which reduces the pressure applied onto the substrate.

Figure 4 compares the cross-sectional shapes of the printed layers from the 3DCP experiments and the numerical simulations. Depending on the printing parameters, the cross-sectional shapes vary between almost-circular profiles (Case 6) to elongated rectangular profiles with rounded corners (Case 1). The layer height is primarily influenced by the nozzle height. Moreover, a lower geometrical aspect ratio (H/D) makes less room below the nozzle for the extruded material, which induces greater side-flows. In addition, according to Eq. (1), the cross-sectional area, A , of the printed layer is inversely proportional to the speed ratio (V/U). Therefore, the layer width increases when the geometrical aspect ratio (H/D) and/or the speed ratio (V/U) are reduced. These trends agree with previous flow analysis for Newtonian fluids published in [11, 12].

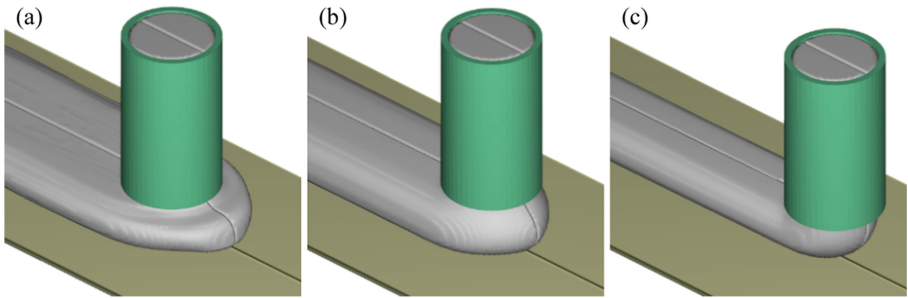


Fig. 3. Mortar surface in the deposition flow simulations. (a) Case 1: $H/D = 0.5$, $V/U = 0.89$. (b) Case 5: $H/D = 0.7$, $V/U = 0.87$. (c) Case 6: $H/D = 0.7$, $V/U = 1.36$.

Overall, the CFD model predicts a lower layer height and a larger layer width as compared to the experimental results. Moreover, all measured layer heights from the experiments are greater than the actual nozzle height, whereas the simulations predict the contrary. In fact, the measured cross-sections from the experiments are very similar to what we would expect with a nozzle height 2.0 mm greater than the prescribed value. Therefore, the difference between the experiments and simulations could be due to the

positioning precision of the robotic arm or, most likely, a small planarity deviation of the build plate. Nevertheless, a positioning precision of 2.0 mm is normally considered acceptable in the context of 3DCP, given the fact that 3DCP platforms are generally designed to fabricate large-scale components with dimensions in the order of meters.

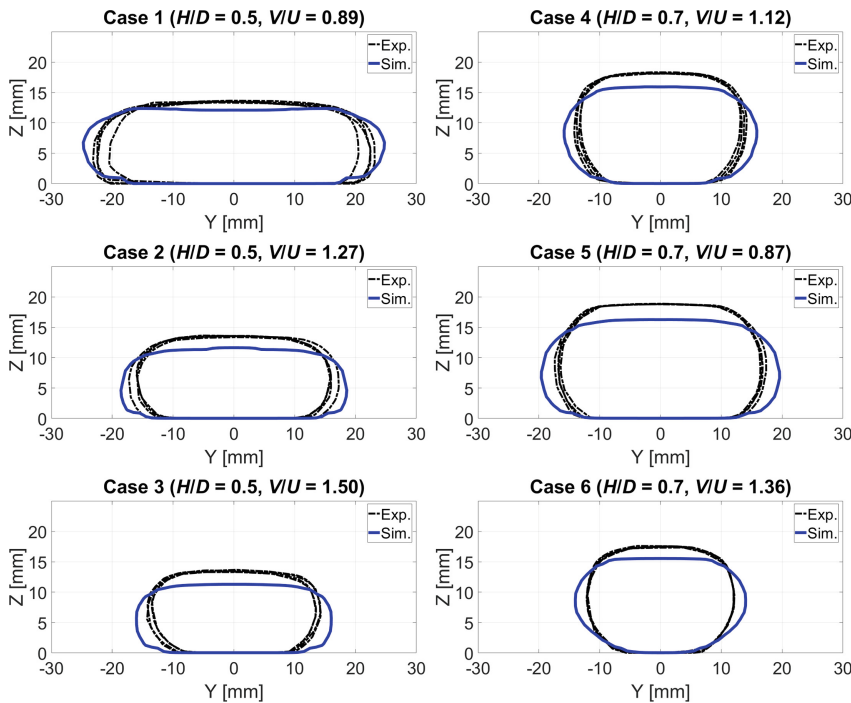


Fig. 4. Cross-sectional shape of the printed segments in the experiments and simulations.

5 Conclusions

This work proposes a numerical model based on CFD to simulate the deposition flow of cementitious materials in extrusion-based 3DCP. The model was used to investigate the influence of the printing parameters on the cross-sectional shape of printed layers. 3DCP experiments were carried out with a cement-based mortar to validate our proposed model. The mortar's rheological properties were characterized by rotational rheometry and modelled with the Bingham constitutive law.

Two non-dimensional parameters have been identified as relevant to explain the influence of process parameters on layer geometry: the geometrical aspect ratio, H/D , and the speed ratio, V/U . Depending on these, the cross-sectional shape of the printed

layers ranges from an almost-circular profile to an elongated rectangular profile with rounded corners. The side flow causing the elongated rectangular shape implies a large pressure applied by the extruded material onto the substrate, which may jeopardize the stability of multilayer prints.

Finally, the observed differences in predicted and extruded layer height opens research questions on whether a visco-plastic model enables a reliable prediction of deposition flow of cementitious materials in extrusion-based 3DCP. Specifically, the use of an elasto-visco-plastic constitutive model could potentially yield more accurate predictions. This analysis is under implementation and will be published elsewhere.

Acknowledgements. The authors would like to acknowledge the support of the Innovation Fund Denmark (Grant no. 8055-00030B: Next Generation of 3D-printed Concrete Structures), as well as the support of COWifonden.

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Automating Concrete Construction: Digital Design of Non-prismatic Reinforced Concrete Beams

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Abstract. The construction industry is responsible for nearly half of the UK's carbon emissions, mainly due to the large amount of concrete used. Traditional formwork methods for concrete result in prismatic building elements with a constant cross-section, but the shear forces and bending moments that beams have to withstand are far from constant along their length. Up to 40% of the concrete in a typical beam could be removed. An iterative optimisation process has been implemented in a parametric modelling framework to generate and analyse optimal forms for non-prismatic beams that take into account the constraints imposed by the fabrication process, namely the use of fabric formwork. The aim of the resulting design tool is to facilitate the adoption of non-prismatic elements by the construction industry.

Keywords: Non-prismatic beam · Reinforced concrete · Automated design · Fabric formwork · Parametric modelling · Structural analysis

1 Introduction

The construction industry needs to change. The UK government has stated that the construction industry should achieve, by 2025, a 33% reduction in initial and whole life cost of assets, a 50% reduction in construction time, and a 50% reduction in greenhouse gas emissions [1].

In terms of sustainability, the construction industry is responsible for nearly half of the UK's carbon emissions [2], mainly due to the use of an extremely large volume of concrete. It is the world's most widely used man-made material, which accounts for more than 5% of global CO₂ emissions. Traditional formwork methods for concrete result in prismatic building elements (such as beams, floors and columns), not because a beam needs to be prismatic to support its load, nor because it is difficult to shape concrete to other forms (it begins life as a liquid), but because existing fabrication techniques rely on easy-to-construct prismatic moulds. 30–50% of the concrete in a typical beam is only there because of the prismatic formwork it was made in, and could be removed [3]. For too long, the industry has used “ease of construction” as an excuse to waste material.

The authors are working on a research project, titled “Automating Concrete Construction (ACORN)”, which aims to dramatically improve whole life construction sector sustainability and productivity by defining a holistic approach to the manufacture, assembly, reuse, and deconstruction of concrete buildings, leading to a healthier, safer, built environment. This research project represents a transitional pathway for low-carbon concrete design, paving the way towards carbon neutrality. This paper shares some early results from the project, particularly its quest to ensure that just enough material is used and no more, by investigating ways of optimising beams and slabs for off-site mass-customization, with a particular focus on the use of flexible formwork for concrete manufacturing. In particular, we present the development of computational design tools with the intent of catalysing the adoption of such an approach by the construction industry. This work precedes the fabrication of 1:1, scale physical test specimens, which will be tested in parallel and reported separately.

2 Related Work

Current digital design and fabrication methods enable the construction industry to produce buildings and building elements with complex and bespoke shapes, evolving from a pre-digital age when orthogonal geometries predominated [4]. Concrete in particular, being the most used construction material, shows large potential to take advantage of such shapes towards greater design freedom, and at the same time a more efficient use of material through structural optimization [5–7], leading to the adoption of non-prismatic concrete building elements.

A large part of the efforts of applying digital fabrication to concrete construction focus on additive manufacturing, commonly called 3d printing [8]. However, concrete 3d printing is relatively novel and raises a number of challenges related to issues such as reinforcement, scalability, and life cycle cost, rendering it unlikely to disrupt the industry in the short term towards a more sustainable paradigm [9, 10].

Since well before additive manufacturing was introduced in the construction industry, concrete elements were traditionally built through casting processes. Subsequently, fabric formwork has been explored as a method for casting non-prismatic concrete elements. A recent review of the state-of-the-art [11] highlights research on fabric carried out in the University of Manitoba [12, 13] and the University of Bath [14, 15], in which beams are manufactured by pouring concrete into a flexible membrane instead of a traditional orthogonal rigid panel formwork. Recent studies on flexible formwork [16, 17] illustrate the potential of combining fabric formwork with digital fabrication as well as digital modelling techniques for improving the accuracy and efficiency of concrete elements.

Digitally driven casting processes have also been successfully applied to concrete construction. In terms of digital design tools, the complex interaction amongst materials and forces in flexible formwork justifies the application of form-finding and optimization processes, integrated with manufacturing constraints. The work of Veenendaal et al. [18, 19] explores the combination of dynamic relaxation, finite element analysis and evolutionary optimization algorithms to determine optimal shapes of concrete structural elements.

As most of these examples illustrate, a formwork approach to concrete manufacturing is considered a viable alternative to additive manufacturing. However, if such methods and processes are to be used in real construction scenarios, they need to be streamlined and flexible.

3 Development of a Design Tool for Optimized Reinforced Concrete Beams

The first step towards manufacturing efficient concrete elements is their design. An iterative optimization process is being implemented in a parametric modelling framework to generate optimal forms for non-prismatic reinforced concrete (RC) elements that take into account the constraints imposed by the fabrication process. This work will culminate with the deployment of a design tool that can be used by professionals in the construction industry, and therefore special attention is being given to the user experience. While the research presented in this paper has focused on beams, the authors are currently exploring ways of expanding to include other building elements such as slabs and columns.

The design of non-prismatic concrete elements will be governed by a design system that articulates three modules, namely generation, analysis and optimization, and is informed by manufacturing constraints (Fig. 1), adopting the approach of previous related research [18]. Such a system allows the evaluation and optimization of the performance of the concrete elements.

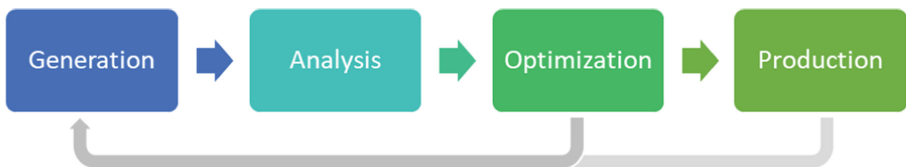


Fig. 1. Modules in ACORN design tool.

Presently, the adopted optimization approach looks for designs that use just enough material for satisfying their design requirement, and no more. In the case of beams, an element's performance is assessed in regard to serviceability, particularly in terms of deflection, as well as checking for flexural strength.

Performance is assessed by the analysis module, in which deflection is estimated using the method of integration of curves [20], as previously applied in the scope of non-prismatic RC beams [21]. This method estimates the deflected displacement of different points along the beam through double integration of curvature in those points. The analysed beam designs are provided by the generation module, which is developed towards flexibility by representing a wide spectrum of shapes and structural configurations.

Since development of the ACORN design tool (henceforth referred to as ACORN) is still in progress, this paper focuses on the first two modules, generation and analysis.

Presently, the ACORN software is being developed within a parametric modelling framework supported by CAD modelling software Rhinoceros (Rhino) and visual programming interface Grasshopper (GH). The tool itself consists of a plugin for GH written in C# using RhinoCommon, a cross-platform.NET software development kit for Rhino. Existing tools for structural analysis were considered for integrating the design system, namely standalone applications such as ANSYS and Robot, or Grasshopper plugins such as Karamba3D, Kangaroo Physics, and K2Engineering. However, shortcomings in these applications to represent a non-prismatic RC beam, as well as their potential to compromise open accessibility to ACORN, pushed towards an integrated solution supported by numerical methods for structural analysis. Once prototyping is complete, the new tool may be re-written as an extension of the aforementioned existing tools to maximise dissemination of the ACORN methodology.

4 Generation Module

The generation module is responsible for creating the shape of a reinforced concrete element represented by NURBS surfaces, as well as information pertaining to it. Since one of the project's research questions is to determine the most efficient manufacturing strategies for producing non-prismatic concrete elements, ACORN needs to be as flexible as possible, hence the decision to adopt NURBS as the representation of geometry.

Presently, two templates are implemented, capable of generating T-shaped, and fabric-formed beams. T-shaped beams were selected as they are fairly common, typically studied in structural design textbooks, while the choice for fabric-formed beams derives from the project team members' expertise in the subject. Note that standard rectangular beams can also be generated using the T-beam template. Moreover, the generation module currently supports point loads and uniformly distributed loads (UDL) along the whole beam, and is limited to simply supported beams. Naturally, as research progresses, the module's capability will be extended to different types (slabs, columns, walls) and sub-types of concrete elements, as well as to additional load cases and support conditions. Defining such elements will build upon the previous work, further enriching the generation module.

In existing structural design tools, structural elements are represented under the assumption that they will be prismatic, or tapered at best, whereas ACORN requires a more flexible representation of non-prismatic elements. Therefore, an effective implementation required the representation of all the elements of the RC beam into a number of classes, enabled by C# being an object-oriented programming language. So far, three main classes have been implemented, corresponding to Beam, CrossSection, and DistributionDiagram. Complying with the Euler-Bernoulli beam theory, according to which the cross-section of a beam remains plane after deformation [22], a Beam object is described in ACORN by a number of CrossSection objects, each of which is in turn associated with a number of calculated DistributionDiagram objects. Additional classes, such as Rebar, help better represent the aforementioned entities.

The representation of T-shaped beams is relatively straight-forward. Given the required parameters, the corresponding T-shaped cross sections are determined, which

in turn are used to generate the beam's shape. Such parameters include flange breadth and depth, web breadth, effective depth, cover thickness, and inset distance. In order to represent a non-prismatic beam, each of these parameters can vary along its length, since they associated to cross sections. Additional parameters pertain to the beam itself and remain constant, namely its span, material properties and number, diameter and type of reinforcement bars used.

While the geometric representation of a T-shaped beam is fairly simple, the generation of a fabric-formed beam implied simulating the behaviour of poured concrete inside fabric formwork. While this can be achieved using physics simulation provided by third-party software, we again opted for a numerical approach. In a first iteration, empirically determined equations were used to approximate the hydrostatic shape as a truncated ellipse [14, 23]. Subsequently, an iterative method was used to form-find the section shape using its top breadth and depth as inputs, corresponding to a variation of the 'elastica' curve, which takes into account the effects of both gravity and the hydrostatic pressure of the poured concrete [21, 24]. The form-finding procedure was further extended to determine the shape of fabric formwork when restrained at a defined depth level with internal ties [25], hence expanding the design space of the beam's shape (Fig. 2). Note that computing the equilibrium shape of two-dimensional sections of the fabric formwork is a simplification of form-finding the doubly curved shape that describes it. However, such simplification has been shown as acceptable [24], and justified since it reduces computation time.

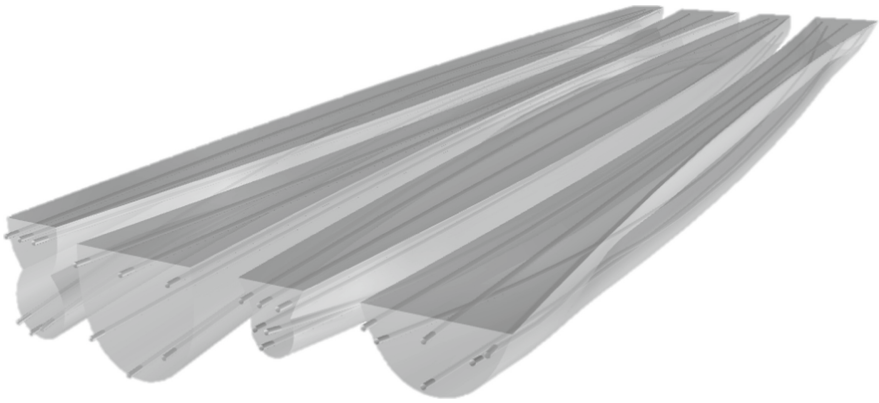


Fig. 2. RC beam designs generated by the ACORN design tool.

The algorithm was tested to replicate the shape of an existing fabric-formed beam, by comparing a model generated by ACORN with a mesh that resulted from 3D-scanning a physical model of a 60-cm long fabric-formed beam [26]. The average deviation between the generated surface and the scanned mesh is 8.6 mm, measured between sampled points in the NURBS surface generated by ACORN and the corresponding closest point in the original mesh. The maximum deviation being is 28.8 mm, and the largest deviations (circled in black) are found at the beam's ends and at

imperfections in the concrete (Fig. 3). While the maximum deviation can be attributed to imperfections in the physical model, the average deviation of 8.6 mm was considered small when compared with the beam's dimensions, namely 1.43% of its 60-cm span and 8.60% of its 10-cm breadth. Nevertheless, an increase in deviation is identified towards the bottom and the ends of the beam (Fig. 3) and should therefore be addressed further afield.

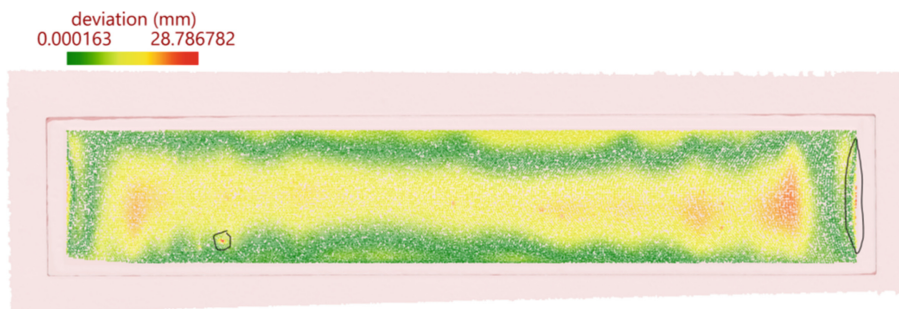


Fig. 3. Geometric deviation between fabric-formed beams produced in [26] and shape generated by ACORN design tool (plan view)

5 Analysis Module

The main purpose of the analysis module is to estimate the maximum deflection for a given beam design. Deflection is targeted over strength since, in the case of buildings, serviceability is often the limiting factor. This is calculated through the method of integration of curves [20]. The main advantage of the implemented module over existing plugin solutions is its capability to analyse non-prismatic geometry, as well as take reinforcement steel into account. The estimation procedure consists of the following:

- divide the beam into a number of equally spaced planar sections;
- for each section,
 - for each strain value within an increasing range of strain values between zero and the ultimate strain value for concrete (0.0035);
 - iteratively determine neutral axis by plotting a hypothetical strain diagram and balancing compression and tension forces both in concrete and reinforcement steel;
 - calculate resisting moment (currently around the centroid of the tension rebar's cross section);
 - plot a graph of resisting moments against curvatures (calculated from slope of strain diagrams);
 - determine curvature from bending moment;
- integrate curvature over beam's length to determine slope;
- integrate slope over beam's length to determine deflection.

One intent in developing the analysis module was to provide as much visual feedback on the analysed parameters as possible, primarily to support validation during development of the tool, and eventually to help designers make informed decisions on the design of a beam based on its performance. Therefore, the beam design is complemented with information on bending moment values, tension and compression forces for each strain value, moment-curvature plots, curvature, slope and deflection values for each section, as well as a summarizing analysis table and key parameters used in generating the beam.

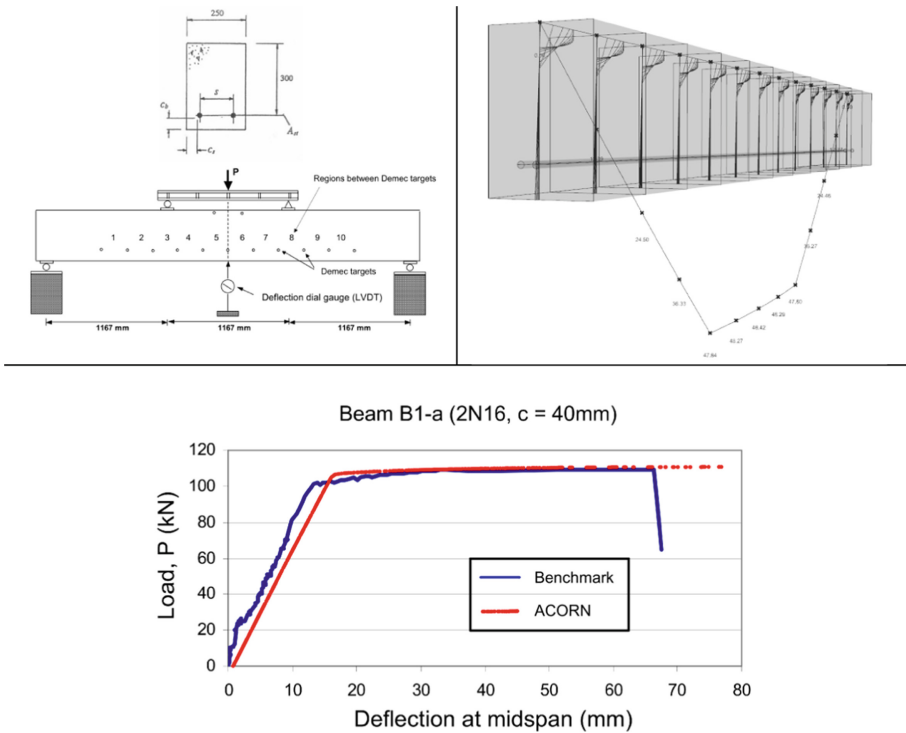


Fig. 4. Analysis module validation – Top left: geometry of benchmark beam (source: [27]); top right: geometry of ACORN beam; bottom: load-deflection plots of benchmark beam and of ACORN beam (adapted from [27]).

The analysis module was validated by comparing its results with published experimental data (Fig. 4), consisting of a series of short-term load tests on reinforced concrete flexural members, to study the development of flexural cracking under increasing loads [27]. Considering these as benchmarks prismatic beams, a beam was modelled in ACORN, replicating the dimensions, support conditions and load case of benchmark beam B1-a. The beam model was then run through the analysis module, generating the corresponding moment-curvature and deflection plots. While not stated in the benchmark study, the simulation considered a yield strength value (F_y) for the

rebar steel of 590 N/mm^2 . A load-deflection plot was then generated in Grasshopper by varying the applied load and comparing the results with the benchmark beams.

Comparing both load-deflection plots shows that their shape is similar: the curves' inflections occur in the same Deflection range, between 10 and 20 mm, and maximum load values are between 100 and 120 kN in both curves. The two plots are fairly approximate, particularly when considering that the benchmark plot results from physical tests and the ACORN plot results from a simulated beam, and therefore we consider the analysis module valid.

Furthermore, parametric studies are being performed in order to a) further validate the analysis module and b) assess the sensitivity of parameters in the generation module. Although the results of these studies will be useful for further developing the design tool, they were not included in this paper due to space restrictions.

6 Conclusions

This paper introduces the ACORN project and presents the ACORN design tool as a work in progress, documenting its current status. As a tool to facilitate the design of sustainable non-prismatic reinforced concrete elements, ACORN is being developed towards three main objectives: flexibility, rigour and usability. Building on previous research on non-prismatic beams, the tool aims at rendering such approach available to current design practices, thus enabling structural designers to design non-prismatic concrete elements with confidence, rigour and speed, and therefore mitigating the obstacles that prevent them from using just enough material. Currently under development, we realize the challenge of honouring those three objectives. Therefore, further development will include the following actions:

- adding beam cross section templates (I beam, girder, generic);
- improve speed until suitable for real-time optimization;
- assess embodied carbon beyond quantity of concrete, including from fabrication transport and assembly strategy.

Subsequently, a full exploration of the optimization module will begin by experimenting with existing optimization plugins for Grasshopper, later looking at additional existing solutions such as topology optimization and, if necessary, developing a custom approach.

As the project advances beyond beams, non-prismatic concrete slabs will be addressed, particularly looking at thin shells, due to their structural efficiency and reduced material. Looking at a wider horizon, it is crucial that our tool is tested in practice, which will be carried out with the support of the dozen Project Partners and growing list of Project Affiliates.

Acknowledgements. The “Automating Concrete Construction (ACORN)” (<http://automated.construction/>) research project is funded by UKRI through the ISCF Transforming Construction programme, grant number EP/S031316/1.

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Free Deposition Printing for Space Truss Structures

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Abstract. This paper proposes a specific extrusion method for 3D printing of mortar called free deposition by the authors. It consists in letting a fine mortar flow through a moving nozzle above a support, here EPS foam. The aim is to obtain a regular lace, thus to avoid instability phenomena like coiling, and ensure a regular diameter, without stretching the lace. A rheological characterisation is proposed and is experimentally tested. This work takes place in the context of the building of space trusses in 3D printed concrete thanks to progressively assembled EPS foam blocks acting as support.

Keywords: Digital fabrication · Concrete printing

1 Introduction

This work deals with the prototyping of space truss structures in printed mortar, involving the assembly of EPS blocks as printing support. This building system has been described in [5] as a masonry concept, see Fig. 1. Once assembled the blocks also protect the curing mortar. The mortar being printed on the blocks, it progressively acquire mechanical strength and can bear its own weight as well as the additional matter above. Yet the blocks support the printing, reducing the need for early age resistance for the mortar.

As such, the printing method differs from the usual concrete printing and can be called free deposition. The other three main printing approaches for extrusion based printing are slip-forming, lace shaping and lace pressing, see Fig. 2 and [6]. Lace shaping relies on the extrusion of a mortar with a yield stress of 1000 Pa that has not to deform. Lace pressing uses admixtures to perform a phase change at the extrusion time and therefore can allow extrusion with early age yield stress of 100 Pa. The pressing relies on the material plasticity to ensure good layer adherence.

Supported by LafargeHolcim and by the Build'in platform.

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F. P. Bos et al. (Eds.): DC 2020, RILEM Bookseries 28, pp. 873–882, 2020.

https://doi.org/10.1007/978-3-030-49916-7_85

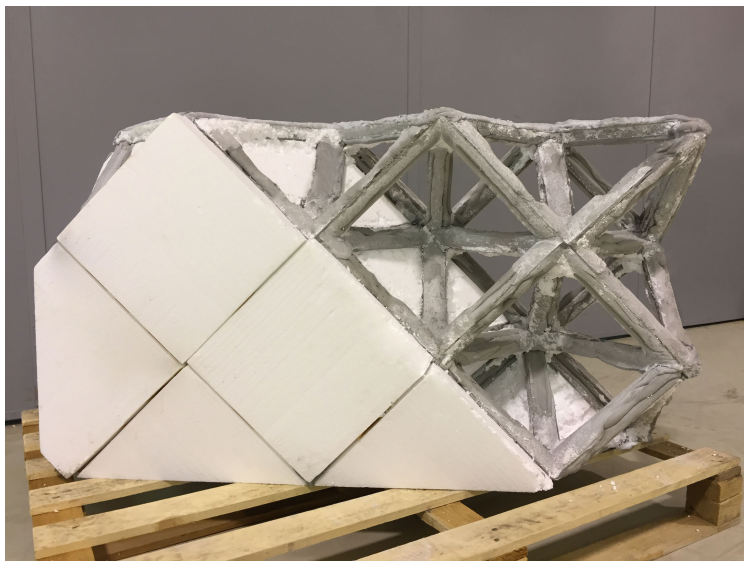


Fig. 1. Space truss masonry wall with robotic extrusion, published in [5]

In the same spirit, free deposition works at low yield stress values at extrusion time to take advantage of mortar deformation in the support. The objectives are to ensure a correct quantity of deposited material, and a correct shape. Lace stretching and coiling must be avoided, therefore, specific deposition regimes are designed depending on the support slope angle, extrusion speed and flow rate, see Sect. 2.

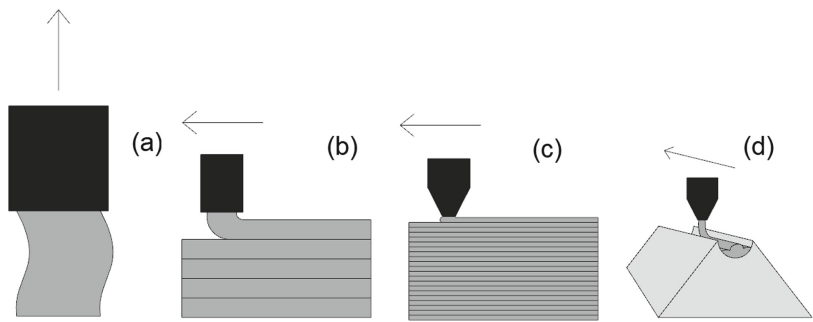


Fig. 2. The four main printing strategies: (a) Slip forming, (b) Extruded shaping, (c) Oriented pressing and (d) Free depositing, published in [6]

2 Process Requirements

2.1 Notations

In the followings of this section, we consider a lace of height h , deposited from a height $H > h$ by an extruder with a circular nozzle of diameter d . The extrusion speed v_e (related to the flow rate Q by $Q = \rho g V_e \pi d^2 / 4$) and robot speed V_r are selected so that $V_e = V_r$ in most of the process, to avoid stretching of the lace. Since no stretching is involved, it is clear that the conservation of mass implies that $d = h$. The main geometrical parameters are represented in Fig. 3. The application studied in this article involves slanted supported, with an inclination θ .

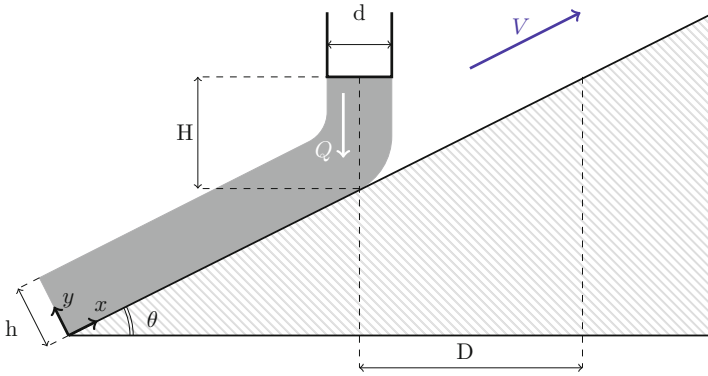


Fig. 3. Notations of the free-flow deposition

2.2 Rheological Requirements

The proposed process is based on the extrusion of yield-stress fluid on slanted supports. The rheological requirements for the extruded material slightly differ from what is usually expected in typical 3d printing applications. In particular, the lace inclination induces a significant shear stress. The maximal stress $\underline{\underline{\sigma}}$ in one lace at simply defined by Eq. (1) (the x and y axes are represented in Fig. 3).

$$\underline{\underline{\sigma}} = \rho g h \begin{pmatrix} 0 & \sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad (1)$$

The component σ_{xx} corresponds to the weight of the lace, whereas $\sigma_{xy} = \sigma_{yx}$ is a shear stress due to the slope inclination. The yield stress τ_c can be compared to the Von Mises stress τ , which is computed in Eq. (2).

$$\tau(\theta) = \rho g h \sqrt{1 + 2 \sin^2 \theta} \quad (2)$$

The flow is initiated when the shear stress exceeds the material yield strength τ_c . This classically yields an avalanche phenomenon that what experimentally observed: the initiated flow yields a thinning of the lace and thus increases dynamic loading on the material below. From a practical point of view, it is thus preferable to keep the shear stress below the yield stress ($\tau(\theta) < \tau_c$). This imposes a constraint on the yield stress of the material described by Eq. (3).

$$\frac{\tau_c}{\rho gh} > \sqrt{1 + 2 \sin^2 \theta} \quad (3)$$

The case $\theta = 0$ is well-known in the literature and ensures that the lace is stable under its own self-weight. One can notice that the Von Mises criterion, classically used for yield stress fluids [4], seems to show that it is possible to print at any angle θ_c provided that the yield stress is high enough, this was explored by the authors [2] in a horizontal printing ($\theta_c = 90^\circ$). In reality, the friction between the substrate and the lace might prevent to reach any arbitrary value of θ_c . For the latter case, a Mohr-Coulomb criterion with low cohesion could be applied to Eq. (1) without difficulty (Fig. 4).

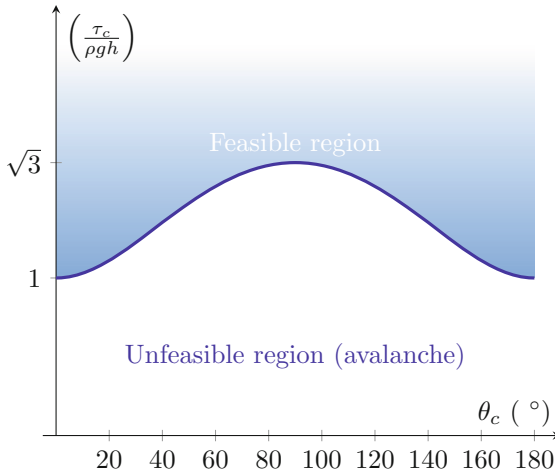


Fig. 4. Feasible domain for yield stress regarding the avalanche phenomenon

2.3 Deposition Height

In the experiments presented in this paper, the nozzle remains aligned with the vertical axis. This brings a constraint on H, D and θ : $D \sim \frac{H}{\tan \theta}$. The nozzle should not collide with the printing bed, which implies that $D > h/2$. Finally, this brings an additional constraint on the minimal deposition height, as shown in Eq. (4).

$$\begin{cases} \frac{H}{h} > 1 & (\text{free - deposition}) \\ \frac{H}{h} > \frac{\tan \theta}{2} & (\text{collision}) \end{cases} \quad (4)$$

The height is also constrained by a dripping phenomenon first described in [3] and revisited for mortar extrusion by some of the authors of this paper [7]. The weight of the lace exerts a tensile force, which is maximal at the tip of the nozzle. When this tensile stress equals the yield stress, the material then rapidly detaches from the nozzle. The stress should thus remain inferior to the yield stress, in order to avoid jet instabilities and coiling. The critical height for this phenomenon is described by the following equation, first derived in [3]:

$$\frac{H}{h} < \frac{\sqrt{3}\tau_c}{\rho gh} \quad (5)$$

2.4 Coiling

The experimental data revealed a coiling phenomenon in several configurations, as illustrated in Fig. 5. Coiling of viscous threads is a well-known physical behaviour [1,10,11]: it is as an instability comparable to buckling (and occurs thus for $H/h > 1$, which is precisely the case of free deposition printing). When the rod is moving at a constant speed, this instability is triggered by the fact that the extrusion speed is superior to the robot speed ($V_r/V_e < 1$). The robot speed was calibrated so as to maintain $V_r/V_e = 1$, yet coiling occasionally occurred in our experiments. For more details on coiling, the reader is referred to [10], which identifies different coiling regimes. In the case of free deposition, stretching is negligible so that we encounter viscous coiling regime.

It was experimentally observed that coiling occurred in the beginning of slopes when the robot is going up. There are two possible explanations. First, the interpolation of speeds is not perfect when abrupt direction changes are at stake, so that the robot speed can punctually differ from the extrusion speed (which is kept constant throughout the printing process). Second, the change between a constant speed horizontal $\mathbf{V}_h$ path and a constant speed inclined $\mathbf{V}_\theta$ path over a time period Δt implies that the nozzle and the mortar in the extruder are subject to a vertical acceleration $V * \sin \theta / \Delta t$. The apparent gravity g' for the concrete is thus

$$g' = g + \frac{V \sin \theta}{\Delta t} \quad (6)$$

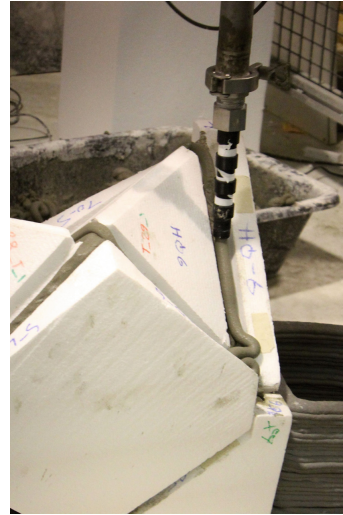


Fig. 5. Coiling pattern (meandering) at the bottom of the gutter.

In practice, we have $V \sim 0.1 \text{ m/s}$, $\Delta t \sim 0.1 \text{ s}$, so that the acceleration can be of 1 m.s^{-2} . In our experimental set-up, the flow rate is controlled with a pump applying a pressure p to the fluid. The flow is controlled if $p > \rho gh$, or in the case $p > \rho g'h$. An increase of g' might thus lead to an overflow $Q + \delta Q$ in an otherwise well-calibrated process. Both explanations advocate for a better control of the robot speed in reorientation areas, in order to increase robotic accuracy and to decrease the dynamic loads applied to the fluid inside the printing head.

3 Experimental Validation

A initial prototype with constant slope angle had been previously executed, see Fig. 1 and [5]. For this work, a curved wall has been designed and fabricated for the sake of slope variation, see Fig. 9.

3.1 Project Description

The prototype is a curved space truss wall, standing on an overall surface of $1 \text{ m} \times 3 \text{ m}$ and with a 1.8 m height. The bars have a diameter of 4 cm and the total weight is of approximately 120 kg . The process constraints as well as performance metrics have been merged in a parametric model, see Fig. 6.

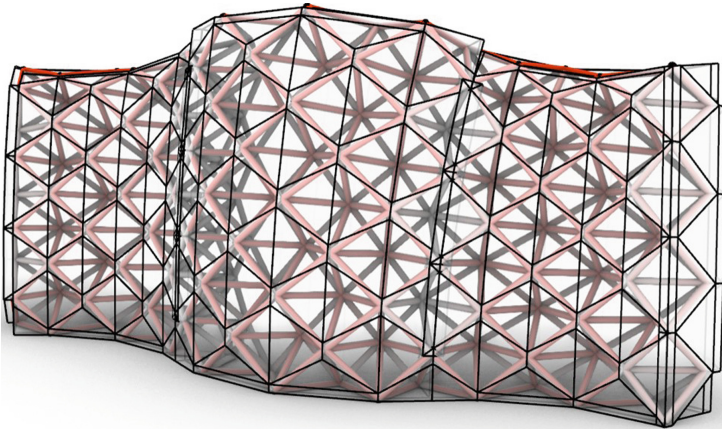


Fig. 6. Parametric design of the curved prototype

The curved tessellation has been obtained from the principal curvature lines of a cyclidic net generated thanks to the method described in [9]. Each block has a unique geometry and has been made by robotic hot-wire cutting, see Fig. 7.



Fig. 7. Robotically hot-wire cut EPS blocks, cut at l'Ecole des Ponts ParisTech (picture: Romain Mesnil)

3.2 Rheological Requirements

The extruded mortar is a bi-component material [8] with an initially low yield stress (around 100 Pa), an accelerator is added to increase the yield stress at the nozzle's tip. The nozzle diameter is $h = 15$ mm, we consider that $\rho g \sim 24 \text{ kN/m}^3$. The maximal angle is $\theta_c \sim 60^\circ$. The minimal yield stress required is found with Eq. (2) and yields $\tau_{c,min} \sim 550$ Pa. The actual yield stress was measured in the beginning of the printing with the drip experiments described in [7] and is in accordance with this theoretical value.

3.3 Printing Set-Up

For this prototype the extrusion has been handled with an ABB 6620 robot and an XtreeE bi-component printing head, and the trajectories/speed mapping generated with HAL Robotics grasshopper plug-in. The EPS blocks were manually placed between each macro layer (horizontal group of blocks), thus creating some precision issues. They were partially solved by calibrating the blocks positions with the robot.

The total lace length L_{lace} is different from the length of the trajectory of the nozzle L_{nozzle} , because the latter is above the blocks, and slope changes create incompatibilities between the lace and toolpath length. This is a practical issue, because free deposition relies on the deposition of an unstressed lace. The conservation of mass indicates that the robot velocity should be adapted so that for each section:

$$V_r L_{nozzle} = V_e L_{lace} \quad (7)$$

3.4 Discussion

On Fig. 8 we can see a correct deposition regime, happening on the bottom macro layers of the prototype. It validates the theoretical approach for free deposition on slope varying support. As the wall rose, imprecision due to manual placement of blocks increased, therefore resulting in deviation from theoretical position of the nozzle. This created some coiling issued, visible on Fig. 9. This was not visible on the first prototype (Fig. 1) due to the constant slope angle and block 3D orientation.



Fig. 8. Free deposition on EPS blocks with correct regime (no coiling, no stretching)



Fig. 9. The completed truss, after removal of some EPS blocks (photo: Stefano Borghi).

4 Conclusion and Perspectives

This article introduces a new extrusion process, called free deposition by the authors. Process requirements for this extrusion strategy are detailed. A prototype with varying support sizes and orientations has been produced.

This approach does not face the same difficulties as other concrete printing methods regarding the reinforcement issue. Layered printing indeed bring anisotropy to the objects it makes, and if reinforcement is to be added to the lace, it will not be possible to orient it in the perpendicular direction. This problem can perhaps be solved by playing with the extrusion path to somehow weave the laces to each other to recreate a global isotropy. In the truss case, the structure has a natural anisotropic behaviour since the forces are oriented along the bars. Lace reinforcement is therefore compatible in principle. Depending on the specific strategy though, some problems remain to be solved.

Among the various possibilities to deal with this generalized printing, layered free deposition of plastic mortar is compatible with the addition of rebars. Indeed, one could imagine, in the same way that the EPS blocks are progressively assembled, to put metallic sticks inside each bar, between the deposition of layers. Correct adherence with the mortar would have to be carefully checked, but does not seem impossible considering the relatively low demand in early age structuration. Fiber reinforcement of the lace is also compatible with such a method and is currently explored by the authors.

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Rapid Composite Formwork: An Automated and Customizable Process for Freeform Concrete Through Computational Design and Robotic Fabrication

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Abstract. This paper presents a series of case studies that incorporate industrial robotics and rapid prototyping tools in the fabrication of custom molds for pre-cast concrete construction. The research documents the fabrication of molds for customizable pre-cast concrete panels in non-standard shapes with unique surface textures. Materials including sand, expanded polystyrene (EPS) and polylactic acid (PLA) are employed to produce robust, reusable, and multiple component molds and inscribe custom surface textures through concrete casting. The fabrication workflows incorporate the limits and constraints of digital processes such as fused deposition modeling (FDM) and robotic hot wire cutting (RHWC). The application of FDM and RHWC to concrete formwork fabrication presents unparalleled opportunities to produce performance embedded prefabricated concrete. In the production of jointing conditions, reinforcing and support structures, and the embedding of conduits and insulating cavities, FDM of concrete formwork in PLA offers an integrated process for an interdisciplinary design and production of smart concrete forms. By combining the flexibility, precision, and speed of RHWC and FDM, this research demonstrates the capacity of this process to efficiently produce high-fidelity, intricate, complex and performance embedded geometries in concrete.

Keywords: Robotic fabrication · Hotwire foam cutting · 3D printing · Concrete casting · Rapid prototyping

1 Introduction

The advent of automation in architecture has provided opportunities for the design and production of increasingly complex assemblies fabricated using a variety of processes and materials and capable of simultaneously integrating multiple functions. The availability of a range of options in terms of production processes means that designers are required to apply as much consideration to the fabrication process as to the design outcome. Readily available customizable software plugins have allowed fabrication constraints to be incorporated within the design space, resulting in a new design paradigm which has been referred to as “Formation Embedded Design” [1]. The feedback loop created by design and production interaction has brought additional responsibilities for designers such as the need to incorporate the optimization of

automated processes, material efficiencies, carbon intensity and life-cycle analysis as design constraints. Recently there has been a growing awareness of the need to apply CAD/CAM technologies to respond to environmental concerns. One area of particular interest to architects is the concrete industry. Concrete is the most widely used construction material in the world and its market demand is predicted to double in the next 30 years [2]. At the same time, the concrete industry is making efforts to reduce the carbon intensity of concrete as a construction material. As this market grows, there will be significant demand for innovation in concrete production that reduces the time, cost, and environmental impact of concrete construction.

Conventional concrete production that involves the use of standardized wooden formwork fails to unlock the full geometric potentials of concrete [2]. Recent work by the Block Research Group has sought to develop new techniques for the design and construction of topologically optimized thin concrete shell structures informed by the exploratory work of Felix Candela [3]. Novel approaches to fabrication such as fabric casting, pioneered by Spanish Architect Miguel Fisac have inspired the recent work of Andrew Kudless in his 'P-Wall' series [4]. Contemporary practitioners are applying new approaches to manufacturing which have afforded greater degrees of freedom and material control [5]. These approaches can be engaged in a manner that optimizes structural performance, limits waste and reduces the labor involved in the construction of elaborate formwork while at the same time unlocking concrete's formal and aesthetic capacities. Integrated design processes which incorporate performance optimization, automated production and composite material assemblies allow designers to embed performance attributes and use materials more resourcefully [6]. While these technologies are often discussed regarding their efficiencies, they also offer designers more opportunities for generating emergent material effects and ornamental designs combining materialization and formation logics [7]. This paper therefore focuses on a combination of design and fabrication methods which leverage digital techniques towards material efficient and performance embedded concrete prototypes that feature unique surface textures. This study is part of an ongoing body of research undertaken by the Laboratory for Integrative Design into material, form, pattern and automated production techniques.

2 Digital Formwork

The digital fabrication of molds for mass-customized concrete components involves multiple constraints such as the inherent material properties, limits of tool positioning, and production costs. In response to these challenges, the production of concrete molds often involves methods that can quickly produce lightweight shapes using cheap and reusable materials.

Robotic hot wire cutting (RHWC) of expanded polystyrene (EPS) is one such approach that enables designers to cut through large volumes at significantly lower processing times, while resulting in highly smooth and low-cost molds [5]. EPS is inexpensive, recyclable, easy to shape [8], and its lightweight properties allow for the development of larger volumes that are easier and quicker to construct [9]. Furthermore, when compared to computer-numeric-controlled (CNC) milling, RHWC is faster, more cost-effective, and uses less energy during manufacturing. RHWC is also considered to be a less wasteful process, since it produces offcuts that can be reused for

future cutting or as packaging for safe transportation rather than shredded down or dusted foam particles [9].

Another digital method that can produce lightweight concrete molds relatively quickly using cost-effective and reusable materials is known as fused deposition modeling (FDM). FDM can employ a wide variety of plastic materials that range in properties - biodegradable, fiber-reinforced, water soluble, flexible, etc. [2]. PLA is a relatively common material used in FDM due to its versatility, low shrinkage factor, and ability to be infinitely recycled or composted [2]. The main interest in using this method in the production of concrete molds is the expectation of new freedom in terms of design geometry as well as new aesthetic and functional features. Moreover, FDM can be used to produce thin, rigid geometry for lightweight formwork, and its precision can reach one tenth of a millimeter [2].

Both EPS foam and PLA can have a second life after being used as concrete molds. EPS can be broken down, melted, and re-molded through a closed-cell process [10], or it can be mechanically broken down into small 3–5 mm pieces to be incorporated into concrete mixes for a lightweight concrete panel [11]. Likewise, PLA can be recycled into new 3D prints as it is easy to clean, and it can be shredded back into pellets for extrusion in new 3D prints [12]. In addition, being made of biodegradable materials, PLA can alternatively be composted [13].

The case studies in this paper thus investigate the applications of robotic procedures and FDM using cost-effective and easily recyclable materials such as EPS and PLA in order to address the growing trends in innovative concrete mold production. Each study aims to balance performance attributes with emergent aesthetic qualities, while demonstrating the capacity for digital technologies to offer flexibility, precision, speed in the fabrication of unique concrete molds.

3 Case Studies

In this section three case studies are presented that have been part of an ongoing research investigation at the Laboratory for Integrative Design at the University of Calgary. The investigations explore the automated processes, material efficiency, and aesthetic expression in the production of concrete molds.

3.1 Bookmatched Panels

The first case study explores how composite concrete molds can be produced through a combination of RHWC and FDM processes. These processes were applied to create a vocabulary of formal and surface effects through an iterative process of digital and physical exploration. A series of highly articulated surface geometries were created by cutting EPS foam with multiple overlaid ruled surfaces which consist of infinite straight lines [16]. The resultant articulations were then trimmed into standardized panel sizes.

This process allows for both sides of the cut stock to be utilized, producing mirrored, or “bookmatched” surface effects. Custom 3D printed PLA frames were designed to clamp around the EPS surface forms and allow for easy release so that the surface panels and frames could be interchanged and reused. This method resulted in the rapid production of low cost and reusable molds that could produce highly intricate concrete forms with a high degree of geometric freedom (Fig. 1 and 2).

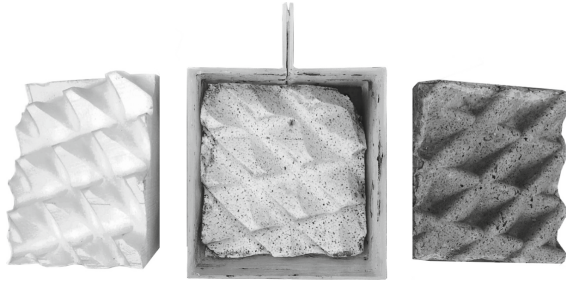


Fig. 1. Assembly of EPS foam texture and PLA 3D print into concrete formwork



Fig. 2. Samples of concrete casting using RHWC textured EPS foam and PLA formworks

The robot mounted hotwire cutter was custom made to be adjustable using T-slot aluminum extrusions that could be reconfigured to adapt to different scales. As well, the cutter was fit with an adjustable power supply to vary voltage and amperage through a nichrome wire tensioned across the frame. The custom cutter was mounted to an ABB IRB 2600 robot with a flat plate that could be easily bolted on (Fig. 3).

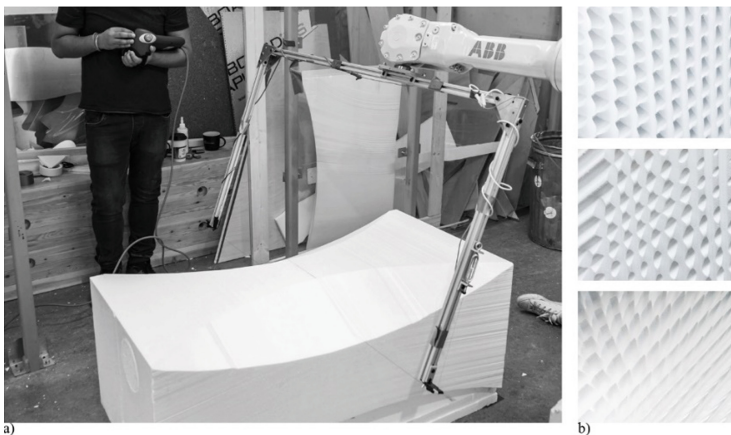


Fig. 3. a) Custom built adjustable T-slot robot mounted hot-wire cutter b) various lighting and textural effects from different cut angles and frequency

Ruled surface toolpaths were generated and simulated using the TACO [14] plugin for Grasshopper 3D [15]. Within this parametric environment, constraints such as tool rotation, the frequency and amplitude of toolpath, approach and retraction vectors, and speed were parameterized to develop toolpaths with consistent kerf (Fig. 4). The toolpaths were simulated to check for collisions and out-of-reach errors. By incorporating these constraints, the toolpaths could be adjusted without time consuming physical tests, extra material waste, or damage to equipment. This also allowed for the optimization of robotic movements to prevent sudden accelerations, stops or joint re-orientations that would result in excessive melting or dragging of the hotwire through the foam. By iteratively developing toolpaths in a constraint-based modeling environment, increasingly complex and readily fabricable geometries were designed and tested before moving into production.

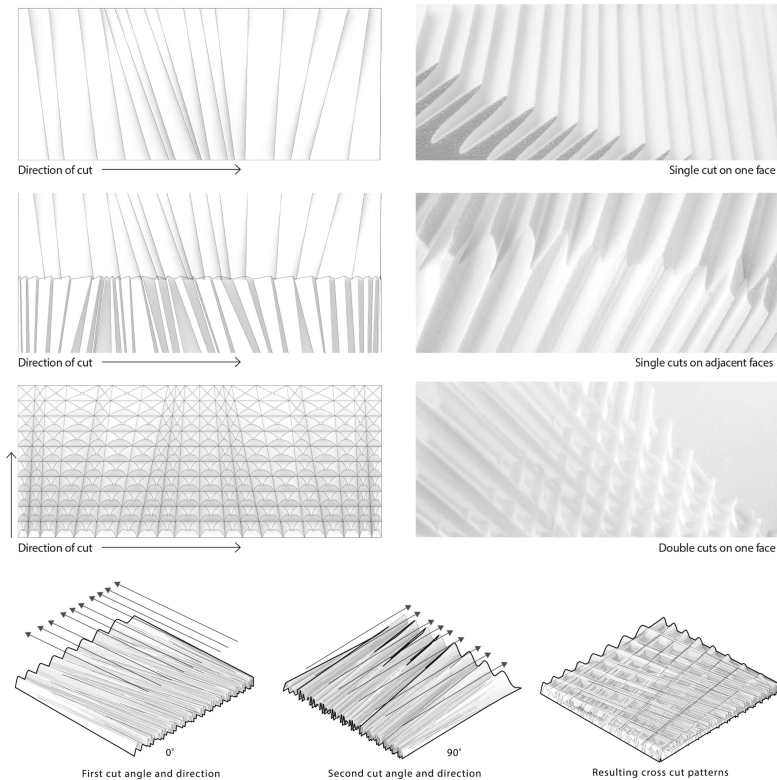


Fig. 4. Increasing complexity of surface patterns with additional and overlapping cut direction at various heights and angles

The 3D printed perimeter frame was printed on a Delta WASP 3MT printer using PLA pellets. The printer features a 1 m³ build volume and can achieve a layer height of approximately 1 mm and a wall thickness of approximately 5 mm, allowing for

prototyping at a construction scale. The 3D printed standardized frames were designed to hold the textured foam surface panels and to be tightened using hand clamps to remove gaps between the wall of the 3D print and the foam. This configuration allowed for easy release of cast prototypes while providing adequate strength to resist hydrostatic pressure and wear and tear from repeated use.

The composite mold fabrication techniques described in these case studies have the potential to reduce material waste and improve the potential recyclability of mold components when compared with standard custom concrete mold making techniques. We propose that composite EPS and PLA molds fabricated using RHWC and FDM printing provide a range of opportunities in terms of aesthetic expression and geometric freedom while at the same time providing benefits in terms of material efficiency and performance optimization. Further, we propose that this system could be tuned to respond to a wide range of aesthetic and functional parameters.

3.2 Volumetric Hotwire Cut Formwork

The second case study builds upon these RHWC techniques for creating articulated surface conditions by investigating how they can be applied to the development of volumetric concrete panel molds to produce architectural elements such as columns, arches and vaults with embedded performance qualities. In this case, ruled surface cuts were mapped onto cylindrical volumes and converted into toolpaths which exploited the range of motion available to a 6-axis robotic arm. The surface patterns resulting from these toolpaths incorporated parameters such as the size and depth of a foam block, amplitude, wavelength and frequency, rotation angle of the tool, and the height at which the robot arm started and finished the cuts (Fig. 5). This exploration aimed at exploiting the degrees of freedom and reachability of the hot wire cutter in order to optimize the cutting of volumetric geometries.

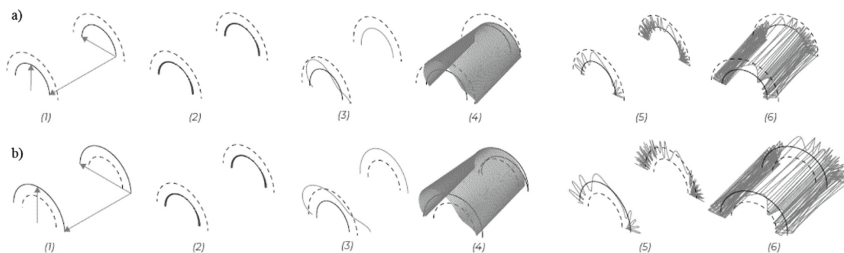


Fig. 5. a) Simulation along the inner curve b) Simulation along the inner curve 1. Defined cut parameters 2. Variable density along the curve 3. Smooth NURBS curve defined using variable amplitude and wavelength 4. Lofted curves to create ruled surfaces 5. High density NURBS curve defined 6. Ruled surface toolpaths for hotwire cutter

This study builds on the formal surface articulation vocabulary developed in the initial case study and extends this investigation by exploring combinations of surface patterns and volumetric geometry. At the same time, it points to the potential for further

research into the integration of additional functions within the formal language. For instance, the composite mold technique could be manipulated to embed spatial requirements for metal frame reinforcement or 3D printed cores for carrying services through the columns. Figure 6 demonstrates this capability and exemplifies an instance where intricate geometry is achieved externally while the internal condition is simplified to easily accommodate a steel frame. This aspect raises questions of expanding the aesthetic catalogue towards realizing a range of technical facilities related to heat exposure, acoustics and thermal performance.

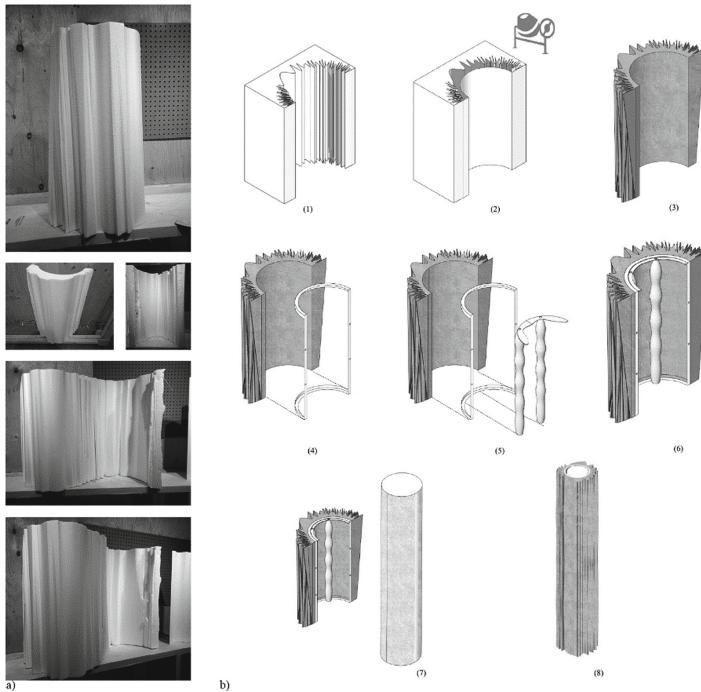


Fig. 6. a) Iterations of volumetric foam cuts and off-cuts b) 1. Existing off-cut foam mold 2. Concrete casting 3. Casted piece 4. Metal framework attached to casted piece 5. 3D printed core for carrying services 6. Single module with attachment and service cores 7. Attachment of module to existing column 8. Panelization of module

3.3 Penrose Panels

The third case study investigates a robotic fabrication procedure that utilizes reusable, modularized molds in the production of bespoke concrete façade panels. Initiated by an interest in balancing waste reduction strategies with customized aesthetics, the study employed FDM using recycled PLA to create lightweight and standardized mold containers to host loose sand for a robotic arm to draw unique patterns into. In this system, flexibility could occur at the level of the sand, while the mold containers

remain constant and could be reused for new sand patterns. The process constantly moved between digital and physical space - digital data defined the mold outputs and robotic movement, and material and spatial data modified the toolpathing sequences. This system also enabled jointing functions to be designed and embedded into the concrete casting process so that the unique panels could be assembled with ease. The investigation used the Penrose (1974) fractal pattern to abstract an image into subdivisions of rhomboids, which also defined mold geometry from the two rhombic figures that the pattern operates with (Fig. 7).

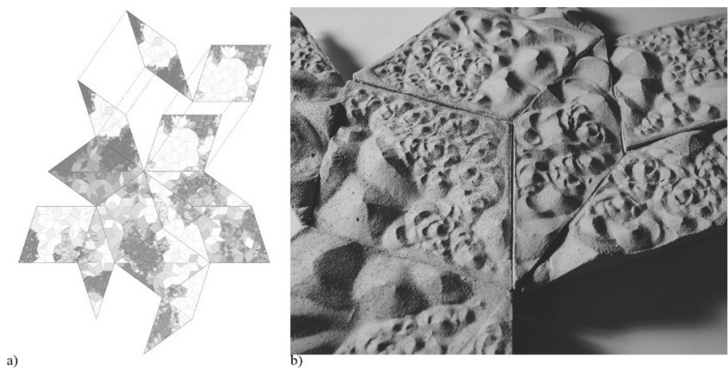


Fig. 7. a) Image abstracted using Penrose fractal subdivisions b) Concrete Penrose Panels

The recycled PLA mold containers were designed to fit into $0.2\text{ m} \times 0.2\text{ m}$ laser-cut plywood bases and be clamped together to contain the loose sand (Fig. 8). The sand would then offer an adaptable platform for a UR10e robotic arm to draw into using a variety of 3D printed and laser-cut toolbits held by a RobotiQ gripper. Of the many different sequences that were developed to translate the patterns into robotic toolpaths, one sequence was chosen to produce all 11 panels since it better leveraged sand's inclination to fall into peaks and valleys around the moving tool (Fig. 9). As a result of the indeterminacy of the material, the workflow formed a feedback loop in which the material characteristics dictated the scale of the Penrose subdivisions, as well as the toolpath angles, depths, and speed.

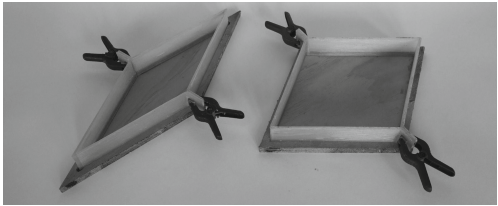


Fig. 8. 3D printed recycled PLA and laser-cut plywood mold containers

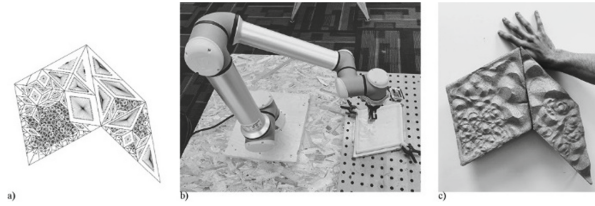


Fig. 9. a) Toolpathing data b) Robotic execution in sand c) Resultant concrete panels

Once the robotic toolpathing was completed, the molds were sprayed with liquid latex to solidify the sand and create a smooth, releasable layer for the concrete to be cast upon (Fig. 10). Laser-cut plywood jigs were also produced to fit on top of the molds so that bolts could be casted into the back of the concrete in locations that corresponded to a universal connection piece – the panels’ edges all shared a common angle that was revolved to create a connecting wheel (Fig. 11). Once the concrete was set, the molds were deconstructed, the latex was peeled off, and the sand and mold containers were reused to create more custom panels.

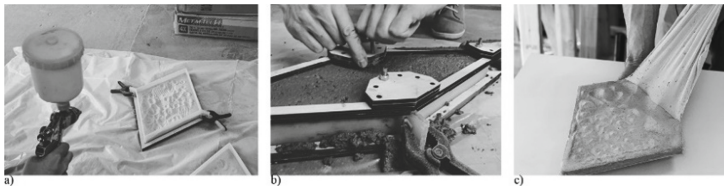


Fig. 10. a) Latex spraying b) Bolt-embedded concrete casting c) Latex removal

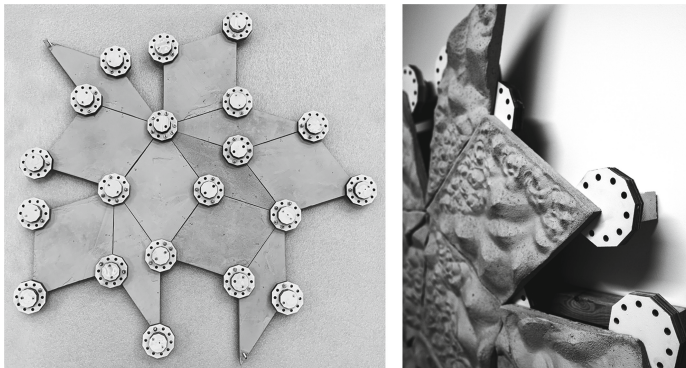


Fig. 11. Universal joint connection wheel on panels

The flexible nature of the sand patterning suggests that further performance attributes could be integrated into the concrete formwork such as solar analyses or acoustic data, and the robotic procedure could potentially produce areas for aperture in the panels.

4 Conclusion

This paper has presented a series of studies that aim to explore how designers can meet the freedom afforded by automated technologies with responsible design intentions that engage critical contemporary issues. Each study has demonstrated ways in which limits and constraints associated with automated fabrication methods can inform integrated and feedback-based workflows for producing complex concrete formwork. Furthermore, various strategies for reducing embodied carbon such as material optimization, recycling, and reuse have also been showcased in the studies, and the use of industrial robotics has been highlighted for their ability to offer designers a platform for developing customized, material-focused, and performance integrated formwork designs.

It should be noted that there are limitations on the ability of FDM printed molds to resist the hydrostatic pressure imposed by higher casting heights. While this limitation is somewhat mitigated by using a large format FDM printer with a larger nozzle diameter and higher wall thicknesses, the actual limitations on casting height using this technique remains to be tested. We have started to investigate some potential methods for addressing these limitations, including: the discretization (subdividing into separate parts [17]) of the formwork, as well as the introduction of additional support elements such as bracing or the use of sand to support the molds [17], or by controlling the concrete hydration and rheology parameters via the inclusion of additives for the optimization of concrete for 3D concrete printing [20] or slip-casting [21] within the concrete mix.

Aside from further exploring highly articulated aesthetic expressions, the flexible nature of these systems could unlock many more opportunities for deploying new datasets or integrated services into concrete formwork formation and materialization. Further research will continue to explore how these approaches can be deployed at larger scales and optimized to incorporate additional functionality in order to integrate performance and aesthetics in a more sustainable approach to composite concrete formwork.

Acknowledgements. The authors would like to thank the University of Calgary School of Architecture Planning and Landscape and the City Building Design Lab for the use of facilities and equipment. The third case study in this paper gained support from the Mitacs Accelerate Funding Program.

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Simultaneous Reinforcement of Concrete While 3D Printing

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Abstract. In order to fully realize the disruptive nature proposed by concrete printing for the construction industry, key challenges need to be overcome to enable the scaling up of this technology. Chief amongst them is the incorporation of reinforcement to absorb tensile stresses and support the structure not only during the printing and curing but also during its service life. Numerous strategies have been tested that allow for embedding reinforcement in the form of filaments, cables, rods or mesh during and/or post printing. This paper explores a strategy for in-situ printing that attempts to embed discrete U-shaped reinforcement elements “staples” vertically interlocking layers simultaneously while printing. A tool, developed for this purpose, trails the extruder and discharges a reinforcement staple that embeds itself into the printed layers. The staples not only penetrate multiple layers, but also interlock to form a reinforcement matrix in the concrete along the vertical axis capable of absorbing limited amounts of tensile stresses. When subject to a 3-point bending test, the reinforced printed elements exhibited an increase in tensile properties. Nevertheless, further research into shape and size of the reinforcement staple is needed to achieve optimum results. Furthermore, with the assistance of robotic fabrication strategies, every position within the print geometry can be identified accurately and reinforcement can be positioned precisely. These positions and their properties/states can be informed by simulating the performance of the geometry under load conditions. The ability to place reinforcement discreetly and accurately can help localize the reinforcement to key stress areas within the geometry thereby optimizing its performance and the use of material.

Keywords: 3D Concrete Printing · Simultaneous reinforcement · Layer adhesion

1 Introduction

Three-dimensional printing (3DP) has been taking over the construction industry swiftly, with materials like concrete and clay being utilized to 3D print large structures. The technology comes in handy as a replacement to traditionally followed methods in construction, as it is: time saving, less labor-intensive and offers the ability to customize on a greater scale [1]. Three-dimensional printing has been introduced into the

construction scale for over two decades until now, yet many challenges still prevent the commercial application of this technology on a large scale. Amongst them include challenges in printing horizontal spans, cantilevers and printing multi-storey structures [2]. Concrete performs well under compression. However, its inadequate ability to withstand tension is only compensated by incorporating reinforcement during the casting process [2]. Herein lies the challenge of incorporating reinforcement into 3D Concrete Printing (3DCP). This is amongst the key obstacles that prevent the technological disruption this technique is predicted to make within the construction industry [3]. Previous tests showed that laying down steel wires over printed mixtures increases their structural strength within the layer itself, but does not address the layer-to-layer discontinuity. While inserting a secondary material while printing enhances layer to layer adhesion [3]. Numerous researchers have explored various techniques by which this can be achieved: in some examples, reinforcement was added manually while printing. In others, reinforcement was pre-printed/pre-assembled and concrete was casted into it. While each of this technique has its own merits, to fully benefit from this technological advantage a new continuous and fully autonomous workflow should be defined.

1.1 Research Overview

This research is proposing a fully autonomous method of simultaneous reinforcement of concrete. This method comprises a tool head that includes a printing nozzle and a stapler. The stapler discharges U-shaped reinforcement filaments into printed layers. Together, these staple profiles form an interlocking network that is embedded into printed layers to form an internal reinforcement matrix that supports the print. The stapling process happens simultaneously while printing and in a periodical manner. This is thought to improve layer to layer connection and support printed structures in the vertical and the horizontal direction (while printing and after curing). Integrating the proposed method with other reinforcement strategies currently being used in the 3DCP industry could have the potential of pushing the geometrical limits of what could be realized; in terms of printing height & maximum inclinations.

1.2 Methodology

This research followed an empirical approach. With a sequence of experiments conducted, and the observation of each feeding into one another. The experiments aimed to explore the following:

- i. Integration of staple reinforcement during the printing process.
- ii. Tool head design and considerations.
- iii. Development of a robotic toolpath.
- iv. Material reaction and tool control.
- v. Staple reinforcement distribution and configuration based on the evaluation of the forces acting on the geometry.

2 Literature

The literature encompasses numerous attempts to integrate reinforcement into 3D printing workflow. These attempts could be categorized into 4 main categories. The first of which is “*Non-simultaneous, layer-specific*”. An example of the first category is that of the Russian company Apis Cor. Where reinforcement bars were manually inserted into the print and grouted thereafter to ensure adhesion with the concrete [4].

The second category of reinforcement found was “*Simultaneous, layer-specific*”. The 3DCP adopted by TU/e is an example of this category. Their setup consisted of a gantry robot equipped with a tool head referred to as a ‘reinforcement entraining device’ (RED). The RED allowed for the introduction of a reinforcement in the middle of the printed concrete in the form of a horizontal filament. This helped in reinforcing prints along the horizontal axis [5].

The third category is “*Non-simultaneous, Non-layer-specific*”. Concrete Formwork, as an example, A project by AI Build, explored the addition of temporary structures, a formwork, that holds casted concrete until it dries out [6]. Allowing for the possibility of realizing curvatures difficult to realize otherwise. In this case, reinforcement supported the structure during the drying phase. However, it did not contribute to the structural properties of the wall itself. Conversely, a different strategy developed by ETH Zurich (Mesh Mould) utilized a workflow of casting concrete in a digitally fabricated formwork, yet with the addition of a 3D printed lattice structure placed inside the formwork as a reinforcement [7]. Similar to the aforementioned technique, Branch Technology [8] were able to print structures that use reinforcement that falls under the same category.

The last category is “*Simultaneous, Non-layer-specific*”. A precedent of that is, Recrete, a project developed by ITECH students at ICD. Where a nail gun was used to incorporate vertical reinforcement in the form of pins into printed concrete [9].

3 Concept Evaluation

To test the effectiveness of the proposed stapling technique as a valid reinforcement strategy, a flexural test was devised to test the reinforcement. Plain concrete is extremely brittle when acted upon by tensile forces. This lack of ductility forces the concrete to fracture at low tensile stress levels. In comparison, reinforced concrete under similar conditions will show great difference between the point when the first flexural cracks appear, and when the beam fractures completely. So, with little difference in the yield (concrete fracture) and fracture values in plain concrete, it stands to argue any difference could be attributed to the behavior of the reinforcement. To test this, an experiment was conducted that utilized two control samples a) non-reinforced concrete beam b) continuously reinforced concrete beam. These samples defined the threshold of tensile performance in the test sample. All samples conformed to the following conditions: rectangular beam of dimensions 242 mm × 16 mm × 30 mm. A 1:1 rich mix of Geolite 40 (produced by Kerakoll, Italy) rapid setting cement and sand. And a 1 mm galvanized wire staples with dimensions of 10 mm × 10 mm. In addition, force was applied using a surface of radius of 15 mm at the center of the beam (Fig. 1 and Table 1).

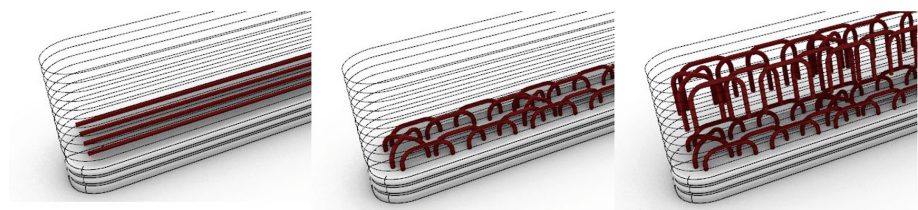


Fig. 1. Testing samples (Left to right): Continuous R, Staple R. Bottom, Staple R. Top + Bottom

Table 1. Tests results.

Test	Sample type	Force (N)	Yield (concrete crack)	Total fracture (steel rupture)
1	Unreinforced	155.0	Yes	–
2	Continuous reinforcement	353.3	Yes	No
3	Staple reinforcement bottom	169.9	Yes	Yes
4	Staple reinforcement Top + Bottom	176.4	Yes	No

The test results showed a near neglectable increase in the peak load of concrete, further tests would be needed to fully validate this as an effective reinforcement technique. As subsequent iterations and tests go, a few changes in the size and shape of reinforcement could help improve the performance of the staple greatly. Key amongst them are:

- I. The lack of adhesion between the concrete and the reinforcement responsible for the fracture can be improved by increasing the horizontal length of the staple.
- II. Increase in overlap between staples and increasing the frequency of occurrence of the staples in areas when high bending moments are generated can help increase the performance.
- III. Depending on the viscosity of the mix used, stapling may result in the creation of small air pockets. Right viscosity has to be reached, to prevent weakened adhesion between concrete and staples.

4 Stapling Hardware

4.1 Tool Head Development

The stapling hardware had to be developed with two goals in mind; Being able to print and staple simultaneously. While being flexible enough to realize a wide range of stapling configurations. Instead of designing a tool from scratch. And due to time constraints, an off-the-shelf industrial electrical staple gun, normally used in wood applications, was purchased and hacked to fit into the robotic workflow; Safety

switches and firing trigger were bypassed to receive a 24 V digital signal that would fire a staple when programmed to do so. The stapler was clamped together with an extruder nozzle. The total tool load came up to 2.7 kg. The clamps utilized were printed using Polylactic acid (PLA) filaments (Fig. 2).

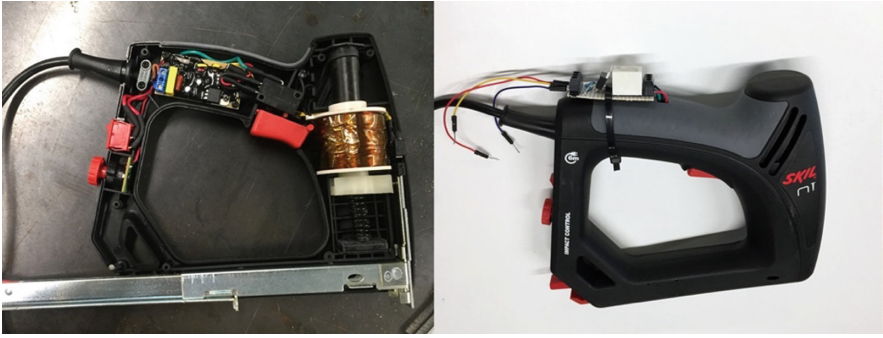


Fig. 2. Hacked stapling tool head.

4.2 Mounting Setups

As shown in Fig. 3, where printing Tool Center Point (TCP) is indicated as a circle and stapling TCP is indicated as a cross. If the tool was to follow the printing path without reorienting, the stapling would always occur outside of the layer boundaries. If tangential reorientation was applied to the stapling TCP, stapling would still miss some of its targets in areas where curvature is too steep. Accordingly, the toolpath was programmed in a way so that the stapling TCP is always projected onto the printing path. Orienting the printing TCP to the vector connecting it with the projected point from the stapling TCP to the printing path. This ensured that stapling was successful within layer boundaries at any given time.

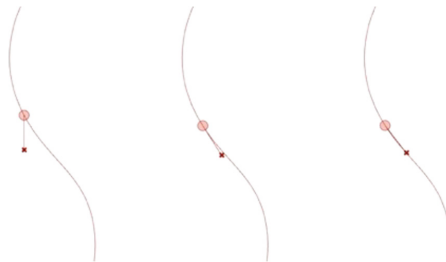


Fig. 3. From left to right: normal path, tangential movement & projected movement.

The previously described configuration was the **“First Tool Mounting Setup”** used in experimentations (Fig. 4). Such setup helped develop a seamless process of printing

and stapling simultaneously. Yet, it imposed restricting limitations in terms of the type of reinforcement strategies possible to be realized; The print path's curvature was restricted by the distance between the printing TCP and the stapling TCP. Moreover, stapling happened in a unidirectional manner, as it was difficult to staple in the return path. In addition, at the beginning of each layer there is a blind spot where stapling cannot take place. Nevertheless, these limitations can be addressed by designing a tool head where the stapling TCP is rotatable around the printing TCP, to add one more degree of freedom.

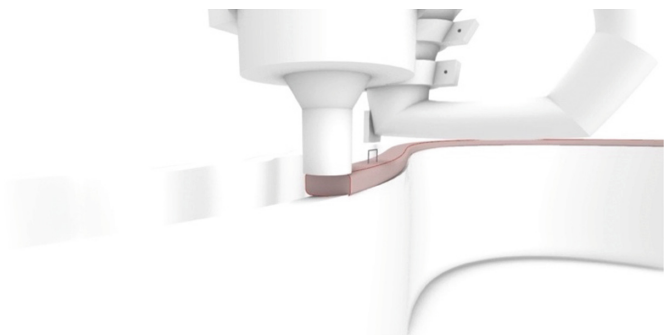


Fig. 4. First tool mounting setup; stapling TCP trailing printing TCP.

For the sake of adding more flexibility in the stapling configurations, using the available setup and without further development of the tool head. A “**Second Tool Mounting Setup**” was tested in which the stapling TCP was perpendicular to the printing TCP (Fig. 5). With such setup, printing occurred first. Following it and after reorienting the tool, an additional second pass of programmed reinforcement in designated areas would follow. The whole process is then repeated until the print is over. A single TCP for each pass resulted in an easier control over the position and orientation of the tool. However, this technique also resulted in an increased time compared to the first setup, and a required delay in the setting time of the concrete.

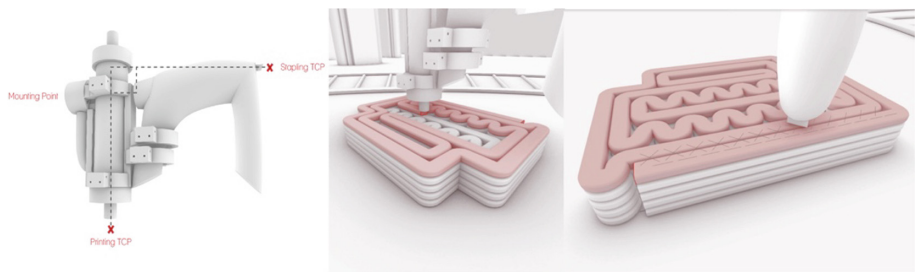


Fig. 5. Second tool mounting setup; switching between stapling TCP and printing TCP.

Although such a setup is not as simultaneous as the previous one, it opened up the way for new types of reinforcement, to name few: having overlapping staples, cross bracing, connecting infills with external layers, and being able to staple at an angle.

5 Prototyping

The tool head developed was mounted on an ABB IRB120 with a payload capacity of 3 kg (Fig. 6). The robot was programmed using “Robots” open source plugin used with Grasshopper®. The configuration of the staples was designed parametrically with relation to the geometry. The generated G-Code encompassed all of the info related to the print path, reorientation of the printing nozzle, and triggering of the stapling hardware.



Fig. 6. Prototyping setup.

In the early stages of the project, the stapling process was envisioned to happen ahead of printing, with staples immersed halfway through the print. Then printing over them with the printing material. Making the staples well integrated with the printed mix from every direction. However, by experimentation, this proved to be impractical; It was observed that due to the high viscosity of the mix, areas surrounding the reinforcement staples were not thoroughly filled. Accordingly, a better approach would be to staple after a layer is printed and immersing the staple all the way through to connect it with “n” number of layers beneath.

Conducted experiments also tried to evaluate the appropriate stapling pressure (which was controllable using the stapling hardware). A conclusion was reached that the U-shape of the reinforcement staples helped in holding back the staples correctly at the surface of the printed layer, under a wide range of impact pressures used. However, it is advised to staple using the least pressure possible between 70–80 psi to prevent running the structure with high pressure from the stapling hardware. Another noted observation was that the layer height should be as low as possible for better

connectivity between layers using the staples. In addition, the distance between the stapling hardware's TCP and the surface of the print should be as small as possible. As bigger distances result in some of the staples being fired at a wrong angle which leads to a poor stapling quality and a poor integration with the print. This could also be attributed to the rigidity of the build. The high recoil generated onto the PLA frame allowed for some vibrations (Fig. 7).



Fig. 7. Distance between hardware and layers (left) stapling in multiple layers (Right).

The material properties and data driven from preceding experiments was then used to design a small-scale beam-like structure with infills (Fig. 8). The reinforcement strategy used involved cross bracing, connecting the double offset of the outer layers & the infill with the outer layers. In addition, the second tool mounting approach explained in Sect. 4.2 was used to allow for more freedom in the realization of the reinforcement configuration.

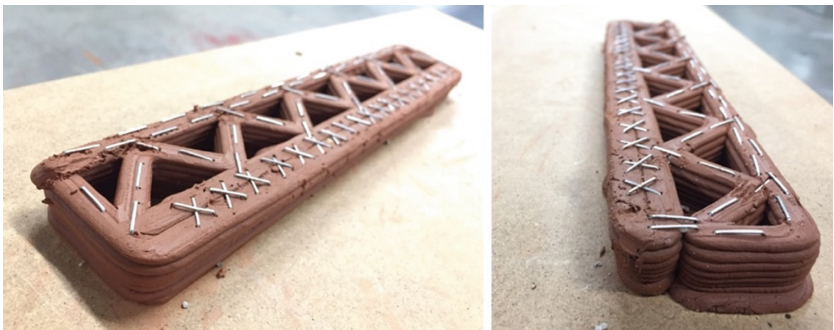


Fig. 8. Reinforcement placed in a clay print for experimentation.

6 Feeding Reinforcement Strategy

One of the key benefits of concrete printing is the ability to automate the entire process. The key advantages this reinforcement strategy offers is the ease and flexibility to evolve from design to fabrication seamlessly. The ability to generate a form, evaluate areas where reinforcement is needed, and fabricate. All can be developed as part of a single continuous workflow. Computational capabilities can be harnessed to develop

complex geometries. The final design is then evaluated for its performance by accounting for the forces acting upon it. A Finite Element Model informs the key areas that require reinforcing. These areas are then isolated and broken into nodes, which are then populated with different staple configurations. Finally, a robotic tool path is generated with all of the commands regarding both printing and stapling (Figs. 9 and 10).

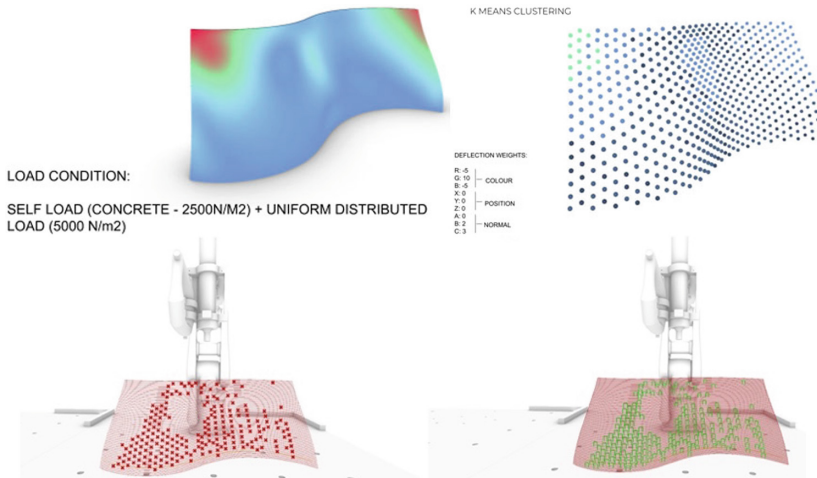


Fig. 9. Example of reinforcement strategy fed into toolpath based on structural simulation.



Fig. 10. Prototype of the previously explained workflow.

7 Conclusion

This research proposed a simultaneous, non-layer specific approach of reinforcement, that utilizes U-shaped filaments “staples” as embedded reinforcement into printed layers. While the results testing the effectiveness of the strategy showed a neglectable increase in its capacity to tackle tensile forces, further testing with a customized staple with a higher horizontal length and increased overlap distance could yield better results. A robotic tool head was developed with the aim of implementing the workflow autonomously. Different mounting setups for the tool head were explored. A conclusion was reached that an optimum setup for the tool head would be one in which stapling TCP trails printing TCP, not the other way around. The addition of an extra

degree of freedom, presented in a rotatable stapling TCP around the axis of the printer's extruder, opens up the possibility to explore a wide range of stapling configurations. In addition, for better stapling quality, the distance between the stapling TCP and the surface of the print should be as minimal as possible. Although stapling works acceptably under a wide range of triggering pressure, it is advised to use as little pressure as possible to avoid ruining printed structures with unnecessary impact resulting from the stapling process. It was observed also that connectivity between layers using staples, works best with reduced layer heights.

8 Future Steps

While initial tests showed a marginal increase in the yield point of concrete with the addition of staples as a reinforcement, further tests are needed to fully validate this approach for large scale applications. These tests include but are not limited to: failure tests under different loading conditions in a controlled environment while using 3D printed and casted specimens with and without staples. Cutting through a cross section of a print with staples, and assessing their integration together with the matrix, as well as the air gaps present, if any. Conducting a pull-out test to measure the bonding strength between the staples and the printed concrete after it has cured. Evaluating the number of staples a print can withstand before it starts having negative effect on the print. As well as the best geometry/material for the staples' filament. On the other hand, the envisioned workflow starts with the evaluation of the geometry to identify key stress areas in certain loading conditions. This data is used to define the type of reinforcement for different areas or states and to develop a strategy for printing. This process can be simplified and automated using machine learning algorithms. Different artificial intelligence (A.I.) strategies like neural networks can be developed to optimize different types of reinforcement in the geometry thereby outputting the most optimum solution which utilizes the reinforcement sparsely. Another type of unsupervised learning called the k-means clustering can be used to group different states/regions of the geometry based on weightage and thus assigning a specific type of reinforcement to it.

Acknowledgement. SIMULTANEOUS REINFORCEMENT OF CONCRETE WHILE 3D PRINTING is a project of IaaC, Institute for Advanced Architecture of Catalonia developed at MRAC, Masters of Robotics and Advanced Construction in 2019 by students: Omar Geneidy, Sujay Kumarji; faculty: Alexandre Dubor, Aldo Sollazzo, Angel Muñoz and Mateusz Zwierzyck; and the support of mentors: Kunaljit Chadha, Eugenio Bettucchi, Raimund Krenmueller and Starsky Lara.

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Additive Manufacturing by Extrusion of Lightweight Concrete - Strand Geometry, Nozzle Design and Layer Layout

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Abstract. In additive manufacturing by concrete extrusion, objects are built up by depositing strands of fresh concrete. The form and size of the strands as well as the order in which they are arranged are decisive parameters for the properties of the resulting construction element. Extrusion of lightweight concrete can be used as a method to construct monolithic structural building elements with an optimized thermal insulation. They may have zones of different functionality and can be augmented by voids to house building technology. This paper discusses the possibilities and limitations in the design of appropriate strand structures and gives recommendations on how strand geometry, nozzle design and layer layout have to be chosen to obtain the desired results.

Keywords: Extrusion · Lightweight concrete · Strand geometry · Nozzle design · Layer layout · Multifunctionality

1 Introduction

Lightweight concrete is a material that unites loadbearing and thermal insulation capacities, allowing the construction of monolithic wall elements without the need for further insulation. By employing additive manufacturing in the fabrication of lightweight concrete elements, the thermal insulation capacity can be further improved by internal cavity structures. The controlled shaping of these structures enables the creation of zones of different density, and thus different properties within the element. Additionally, internal ducts and voids can be implemented to add further functions of building technology. This way, by combining lightweight concrete and additive manufacturing, building elements can be created which are multifunctional in many respects [1].

Additive manufacturing with lightweight concrete can be realized in different ways [1, 2]. Generally, all known processes of additive manufacturing with concrete are suited. This includes selective binding (selective cement paste intrusion, selective cement activation [3]) as well as deposition processes [2, 4]. Concerning the materials, foam concrete [5] and lightweight aggregate concrete [6] have been investigated.

This paper focusses on the extrusion of lightweight aggregate concrete, though some of the discussed aspects can also be applied to concrete extrusion in general.

In concrete extrusion, objects are built up by depositing strands of fresh concrete. Form and size of the strands and the order in which they are arranged are decisive parameters for the properties of the resulting construction element. With regard to the level of multifunctionality targeted here, it is reasonable to explore the use of fine strand patterns.



Fig. 1. Additive manufacturing of a wall element with internal cell structure by extrusion of lightweight aggregate concrete. Aggregate: expanded glass granules with a maximum of 2 mm grain size; nozzle: round opening, 15 mm in diameter, fabricated by STL, fixed orientation.

In this paper, these issues will be discussed referring to our own research on additive manufacturing by extrusion of lightweight aggregate concrete in a layer by layer process (Fig. 1), with both expanded glass granules and wood chips as aggregates. Three topics will be addressed: strand geometry, nozzle design and layer layout.

2 Strand Geometry

2.1 Strand Dimensions (Width and Height)

The *strand width* has to be determined with regard to the layer layout. Strands may at maximum be as wide as the complete layer, in order to form the part in one single path [7, 8]. As the width of the strands is reduced, the geometric freedom increases. Figure 2 shows an example to illustrate the impact of the strand width on the design freedom for the layer layout. Both pictures show one layer of a lightweight concrete wall element, each with the dimensions of 1,250 mm × 500 mm. The strand width differs and

amounts to 50 mm in the variant on the left and 25 mm in the variant on the right. While both variants have the same filling ratio (material/void) of about 70%, in the variant on the left this is accomplished by 6 cells and in the variant on the right by 45 cells. It is evident, that with a fine pattern as in the variant on the right, the possibilities to design the layout of a layer are significantly higher.

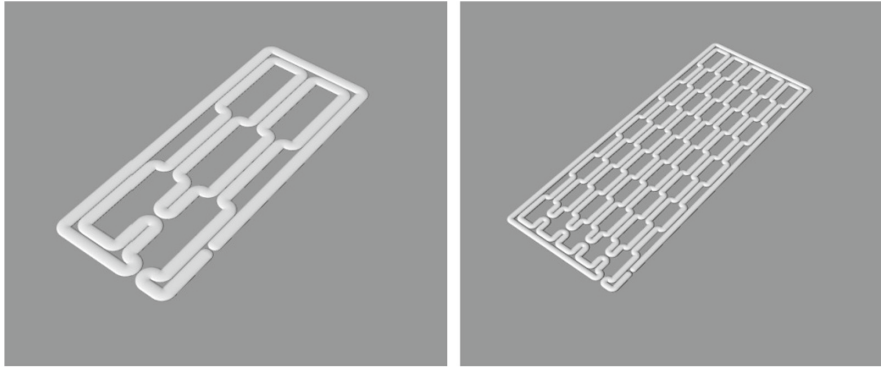


Fig. 2. Two different layer layouts with equal filling ratio (material/void) and strand width of 50 mm (left) and 25 mm (right)

Strands with a narrow width, however, lead to long travel paths and this way to slower processes. The stability on a single strand scale may suffer, especially in areas with overhangs.

The *strand height* determines the layer thickness. The lower the layer thickness, the higher are resolution and surface quality. The lower limit of the layer thickness is determined by the maximum grain size. Considering that in depositing a new layer, the grain can easily be pressed a little into the layer below, the minimum layer thickness can be chosen slightly below the maximum grain size. Lowering the layer height can be advantageous for stability and buildability. However, it has to be considered that layers of lower height lead to a slower building rate. In order to obtain the same building rate as with thicker layers, the overall process speed must be increased accordingly, which may require changes in material design.

2.2 Strand Profile

The form of the cross section of the strand (strand profile) mainly influences the interaction between strands and the surface quality of the work piece.

In general, two types of strands can be distinguished: *round strands* and *profiled strands*. Round strands are produced with simple nozzles with a fixed orientation and a round opening. These strands have an oval cross-section with the typical, convexly curved flanks. In the case of profiled strands, the profile of the strands can be controlled to a certain extent by selecting the appropriate nozzle cross-sections. In doing so, the flanks can be shaped in a straight, concave or other way. However, if twisting of the

strand in corners by the use of a nozzle with fixed orientation [9] is to be avoided, the nozzle must be continuously aligned to the tangent of the machine path, which means an additional technical effort. With regard to that, it should be examined which requirements are to be placed on the strand profile. While the horizontal joints between strands of two consecutive layers will always take on a more or less plane shape, a distinction must be made concerning the vertical flanks of the strands. Three different situations can be distinguished:

- The flank of the strand is part of the outer surface of the component.
- The flank borders on a cavity located inside the component.
- The flank borders on the flank of another strand.

If the flank of the strand is part of the outer surface of the component, it has to contribute, above all, to the surface quality of it. In the case of low layer heights, the vertical resolution is high, making the form of the flanks less significant for the overall surface quality. With thicker layers, it may be desirable to shape the flank in accordance with the desired geometry of the component surface. In the case of components with flat vertical surfaces, this can be achieved comparatively easily by means of appropriately shaped nozzles or molding tools (trowels). In the case of components with freely shaped surfaces, however, this requires considerable technical effort.



Fig. 3. Test sample fabricated by extrusion of lightweight aggregate concrete. Aggregate: expanded glass granules with a maximum of 4 mm grain size; nozzle: rectangular opening with toothed rim, 44 mm × 11 mm, rotatable, fabricated by STL.

In situations where the flank borders on the flank of another strand (regardless of whether they are touching while parallel or while converging on one point, see also Fig. 5), a good mechanical bond between the two strands should be achieved. This will most likely be the case with straight, vertical flanks. However, a good bond without cavities can also be achieved with round strands, provided the yield stress of the fresh concrete is low enough, so that the material can flow into the space between the strands.

No special requirements for the flank geometry can be derived from a situation where the flank borders on a cavity located inside the component. The same is true for situations where strands are crossing.

It can be concluded, that with low layer thicknesses and a low yield stress combined with a high structural buildup, satisfactory results in terms of geometric freedom, surface quality and strength are achievable with round strands. Surfaces show the typical ridged structure, regardless of whether they are vertical, inclined, flat or curved. With strands, which are formed by levelling the upper surface with the nozzle rather than by laying down material, the dimensional accuracy in z-direction can be well controlled. Reducing the distance between nozzle and the upper surface can also contribute to the bonding between layers [10].

Profiled strands with rectangular cross sections promise a good bond at the vertical joints, even with higher yield stress of the fresh concrete. The surface quality will appear slightly different compared to that of round strands. For components with vertical, flat surfaces, there will be an improvement in the surface quality, for inclined and free-formed surfaces, a stair effect will appear (Fig. 3).

3 Nozzle Design

Nozzles for the extrusion of fresh concrete have to be designed according to the required strand geometry (see Sect. 2) and desired freedoms concerning the layer layout (see Sect. 4).



Fig. 4. Left: End effector with (from left to right) mortar hose coupling, pneumatic valve, toothed belt pulley for rotating the nozzle, rapid nozzle fastener, stainless steel nozzle. Right: Nozzles with different openings, fabricated by STL.

They can be differentiated according to a variety of criteria:

- Size of the opening (e.g. in mm^2)
- Shape of the opening (e.g. round, triangular, rectangular, planar, spatially curved) (Fig. 4, right)

- Shaping of the rim of the opening (e.g. smooth, toothed)
- Slope of the flanks (steep or moderately inclined)
- Orientation of the opening (e.g. downwards, backwards, slanting)
- Kinematics of the nozzle (e.g. rotatable (Fig. 4, left) or not)
- Valve (nozzles with (Fig. 4, left) or without a valve)
- Additives (nozzles with or without devices for adding additives)
- Number and arrangement of trowels (e.g. one or two trowels on the side, trowels on three sides)
- Shape of the trowels (e.g. flat, curved)
- Kinematics of the trowels (e.g. fixed, hinged, freely movable)
- Number of nozzles (single nozzle, print head with several nozzles)
- Material (e.g. polylactide (PLA), Polyoxymethylene (POM), steel)
- Manufacturing process (milling, turning, fused filament fabrication, stereolithography)

The aspects size and shape of the opening and the possible need to rotate the nozzle (kinematics) have already been addressed in terms of resulting strand geometry in Sect. 2. With regard to the intended multifunctionality of the lightweight concrete elements, this is achieved by fine internal structures, realized by interwoven strand patterns (see Sect. 4). Two other criteria need to be commented on here. Solutions with fixed trowels are not suited for these kinds of structures, because the trowels will damage already deposited strands in areas of touching or crossing strands. If trowels are considered beneficial, solutions with movable trowels have to be chosen [11–13]. For the same reason, nozzles with openings pointing downwards can be regarded as mandatory, as e.g. nozzles with openings pointing backwards [7] reach into the space of the layer in production and will interfere with already fabricated structures.

4 Layer Layout

4.1 Loops

The fabrication of the 3-dimensional work piece can be realized as a single, uninterrupted extrusion line/thread, when each single layer is designed as a loop, where the

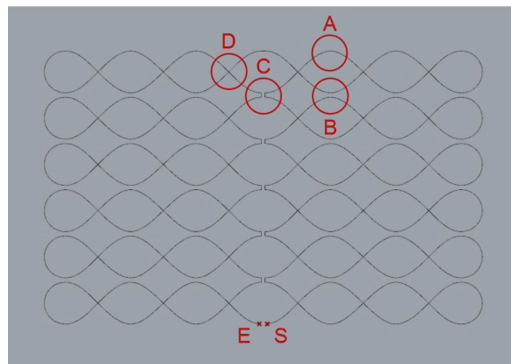


Fig. 5. Layer layout as loop with different strand situations

endpoint E lies adjacent to the starting point S of the same, and thus of the subsequent layer (Fig. 5). This is considered to be advantageous, as stopping the flow of fresh concrete (e.g. by a valve), which bears the risk of defects by material inconsistencies or even blocking, can be avoided.

4.2 Strand Situations

In designing layer layouts, different possible situations inside the pattern have to be considered: Strands may be freestanding (Fig. 5 A), touching while parallel (Fig. 5 B), touching while converging on a single point (Fig. 5 C) or crossing (Fig. 5 D).

Large sections of structures formed by layering of freestanding strands tend to have a poor stability due to the risk of buckling. In this case, curved strands perform better than straight ones. Joining strands by crossing or touching are means to increase the stability of the structure.

To achieve a sufficient bonding, the distance between touching strands (Fig. 5 C and D) has to be chosen carefully and may be different for the two different situations. Material with a high viscosity can be pulled in the direction of the nozzle's travel path and will, therefore, deviate from its planned position. This is especially critical for strands touching only at a single point (Fig. 5 C). As discussed in Sect. 3, the feasibility of these situations (Fig. 5 A–D) depends on the nozzle design. Nozzles with trowels e.g. are not suited to form crossing or touching strands (Fig. 5 B–D). Similarly, for crossing strands (Fig. 5 D), the distance between nozzle and strand must be considered, as the material will pile up if allowed.

4.3 Structures with Constant Layer Pattern

As long as structures are prismatic and shaped without overhangs, they are built up by a sequence of equal layer patterns. Nonetheless, the path in which the strand is deposited may vary from layer to layer, adding to the stability of the part by an offsetting of joints (Fig. 6, left).

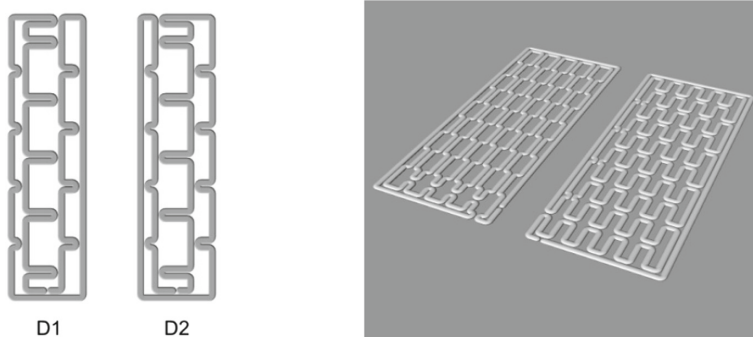


Fig. 6. Layer patterns. Left: Two consecutive layers of an object with the same layer pattern but different extrusion paths. Right: Two different layer patterns of wall elements with the same density but different performance concerning thermal insulation.

The single layer layout will be designed in a way that it serves the desired functions, which may be of e.g. structural, thermal or acoustic nature. Small-meshed patterns have a higher density, which leads to higher strength, while wide-meshed patterns provide better thermal insulation.

A variety of regular patterns that are composed only by a single type of polygon (e.g. triangles, rectangles, hexagons) are feasible. Components manufactured by the use of such patterns will exhibit consistent properties over the entire cross section.

Different patterns of the same density may still perform differently depending on the geometry of the pattern. The right pattern of the two cross sections of a wall shown on Fig. 6 will offer e.g. higher resistance to heat transmission across the component than the one on the left. Even though both patterns have internal voids to increase thermal resistance, in the left pattern the bars between the cells are aligned, forming a thermal bridge. In the right pattern, the thermal bridge is diminished by the offset of the cells.

The pattern can vary in geometry and mesh-size in different areas of the layer (Fig. 7, left), leading to zones of different functionality ('functional grading'). The change from one zone to another can also be gradual (Fig. 7, right).

4.4 Structures with Varying Layer Patterns



Fig. 7. Additive manufacturing of wall elements with internal cell structures by extrusion of lightweight aggregate concrete. Left: Element with zones of varying density and slot for appliances of building technology; aggregate: wood chips, 0.5–1.6 mm (sieve opening); nozzle: round opening, 20 mm in diameter, fabricated from POM by turning, fixed orientation. Right: Element with closed, air-filled cells, gradually changing in size (design and digital model by Fabian Jaugstetter); aggregate: expanded glass granules with a maximum of 2 mm grain size; nozzle: round opening, 15 mm in diameter, fabricated by STL, fixed orientation.

As far as material and process allow the formation of overhangs, a deviation of the layer layout from one layer to the following is possible, which leads to a drastic increase of geometric freedom. Examples for applications are wall openings, horizontal ducts, and closed air-filled cells, which may be advantageous for structures with an optimized thermal insulation capacity (Fig. 7, right).

5 Conclusions

Additive manufacturing by extrusion of lightweight aggregate concrete can be utilized to fabricate monolithic, multifunctional building elements that unite structural and thermal insulation properties and which can be augmented by further functions.

By the choice of appropriate nozzles and, with that, suitable strand geometries, a high degree of geometric freedom for the design of the layer layout and thus the outer shape and the inner structure of the object can be achieved.

Simple rigid nozzles with a round, downwards pointing opening of a diameter of 15–20 mm have proven to be satisfactory. If a better control over the strand geometry is required, rotatable nozzles with a rectangular or otherwise shaped opening can be chosen.

This way structurally and building-physically optimized building elements are feasible. Related research has to combine digital optimization tools with the design rules derived from the topics discussed in this paper. Such simulations will have to be complemented by testing of additively manufactured physical specimens.

The range of possibilities will be significantly widened as the feasibility to build overhangs increases. Corresponding research on the material and process side is encouraged to push this issue.

In addition, it should be taken into consideration that the scope of action could be further expanded by a deviation from the usual horizontal layers.

When it comes to the speed of the process, the customary use of single nozzles has to be questioned. Multiple nozzle systems can be seen as a promising instrument to speed up extrusion processes.

Acknowledgements. The research documented in this paper was conducted within the project, Additive Manufacturing of Multifunctional, Monolithic Wall Elements by Extrusion of Lightweight Concrete'. It was funded by the innovation program 'Zukunft Bau' of the Federal Ministry of the Interior, Building and Community, Federal Republic of Germany (project number SWD-10.08.18.7-17.14).

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Extrusion Nozzle Shaping for Improved 3DP of Engineered Cementitious Composites (ECC/SHCC)

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Abstract. This paper focuses on the development of a nozzle steering and shaping system for concrete 3D printing (3DCP) of Engineered/Strain Hardening Cementitious Composites (ECC/SHCC). The investigation highlights the development of an integrated system that includes robotic end-effector tooling, automated control associated with the delivery and deposition processes, as well as multi-axis nozzle steering for enhanced surface quality of the printed components. The results are discussed along with demonstrated prototypes. While significant improvements to the speed and efficiency of 3DP cementitious materials have been developed in recent years, only a few precedents, discussed in the paper, have aimed to improve geometric surface quality of the final printed components. In addition to improving the surface quality, the designed extrusion shaping process has the potential to improve mechanical performance of ECC by maximizing interfacial surface area and improving fiber alignment. Material effects will also be discussed in relation to the development of the overall system. An overview of the geometric capabilities and limitations of the proposed system will be presented in comparison with existing 3DP techniques.

Keywords: 3D concrete printing · ECC/SHCC · Computational design · Digital fabrication

1 Introduction

Additive manufacturing (AM), more commonly referred to as 3D printing, is poised to revolutionize the building construction industry. It has attracted significant commercial interest due to its potential to reduce time, labor, and material use, while improving overall building performance through computational optimization. The most promising application for the construction industry centers on concrete, where a significant portion of the construction cost is attributed to formwork production, often as much as 50% of total project cost [1]. Concrete 3DP (3DCP) holds the promise of reducing or eliminating the need for molds. One challenge to this process is that layer-based extrusion approaches do not yield surface finishes which can compete with molded concrete. While hybrid approaches, such as robotically post-finishing a deposited

surface [2] or troweling [3] have been tested, there are limitations to the geometric freedom of the printing process and overall formal complexity of the printed part.

Another widely discussed challenge to the adoption of 3DCP is the difficulty of combining the process with existing methods of reinforcement, which is required due to the brittle nature of concrete materials. Novel approaches to overcoming this limitation have been explored, including embedding continuous reinforcement, such as steel cables, as well as post-tensioning of structures [4]. Both approaches present compromises in the printing process or limit the design freedom of 3DP structures. Engineered Cementitious Composites (ECC) (also known as Strain-hardening Cement-based Composites, SHCC) are a class of materials which were developed to challenge the notion of concrete as a brittle material, and have been shown to possess significant ductility (as much as 400x that of normal mortars) [1, 5]. Not surprisingly, a growing number of research teams have focused on adapting 3DCP to take advantage of the self-reinforcing properties of ECC with polyvinyl alcohol (PVA) or polyethylene (PE) fibers [6, 7].

This paper will discuss the development of a robust system for 3DP ECC, including an extrusion nozzle shaping system and its influence on both the overall geometric form and surface finish. This research has multiple, inter-related goals. The first is to develop a 3DCP system compatible with ECC, which maximizes the geometric freedom of the deposition process while improving the surface finish to approximate that of cast concrete. The second goal is to prototype examples of full-scale building components that leverage the capabilities of the robotically controlled printing process. The paper will elaborate on the integrated design to fabrication methodology that enables direct translation from digitally designed geometry to machine toolpaths, taking advantage of the additional degree of freedom of the steering system. The developed software also enables geometric features such as variable layer height, and digitally simulates the printed result along with metrics such as material utilization and time estimation.

2 Challenges

2.1 Material, Process, and Geometric Considerations of 3DP ECC

The challenges of 3DCP are widely discussed and have been the subject of extensive research, particularly in relation to time-dependent rheological properties like pumpability and buildability. These challenges are typically identified within the three phases of 3DP, namely, mixing, transport, and placement - where equipment, process, and material have corresponding effects upon one another [8]. At a typical loading of 2% fiber by volume there is a significant impact on the rheological characteristics of the material. Additionally, there are secondary impacts that high fiber and high fly ash mixes have on the pumping system. While the addition of fly ash is known to increase pumpability, significant increases can cause bleeding. This effect, coupled with high fiber volume fractions, risks separation and blockage of flow in the system.

The material transport system is one of the fundamental components of 3DCP technology. The most common pumps used are either of the progressive cavity or

peristaltic design. While both are considered positive displacement pumps, they each possess advantages and disadvantages. Progressive cavity (PC) pumps are known to work well with highly viscous materials and transported solids. They have highly linear flowrates relative to pump speed. At the upper end of the viscosity range this linearity depends on the inlet pressure being maintained. In the case of transported fibers, PC pumps have challenges which will be discussed in Sect. 3.1. Peristaltic pumps have similar capabilities for high viscosities and solids but have the disadvantage of significant pulsation, though this can be mitigated with pulsation dampeners. Their relatively open flow design improves the passage of fibers through the pump. It is also worth mentioning that peristaltic pumps, without any disassembly, are easier to clean and flush, whereas PC pumps require the removal of the stator from the rotor in order to remove any concrete and fiber buildup.

The other fundamental component of 3DCP is the deposition or placement process, which is coupled with a motion control system. Various approaches using CNC and robotics have been studied [3, 8, 9]. In order to achieve the goal of maximum geometric freedom, a minimum of 5 degrees of freedom (DOF) is recommended. In the case of extrusion nozzle shaping approaches, this increases to 6 or more. In order to support more complex toolpath geometries, such as branching structures, it also becomes critical that the deposition system be able to dynamically control the start and stop of the extrusion. There are two primary approaches to controlling this behavior, one utilizing a valve, and the other utilizing a frequency-controlled pump (and some approaches combine the two). A valve, being compact, can be located near the extrusion point, which improves the dynamic response of the system. Typical valves used in 3DCP are “pinch-valves”, but more study is needed to determine their compatibility with ECC. A frequency-controlled pump has the added advantage of allowing for different speeds of extrusion, either to match different speeds of the motion control platform, or to extrude layers of different thickness or width. Depending on the overall system arrangement, such as a supply pump feeding a long hose to the placement head, this approach may not offer enough control over start/stop dynamics. A critical component of this research is to explore an integrated approach which has highly dynamic control of material flowrate and start/stop behavior.

2.2 Surface Finish

In more common AM technologies, such as Fused Filament Manufacturing (FFF), surface finishes are governed by the layer resolution; smaller layers lead to a higher fidelity between the design and the manufactured component. Experiments during this research have utilized layer thicknesses ranging from 5–15 mm, with the typical thickness being 10 mm in order to strike a balance between material demand and the overall scale of the prototypes. In the case of full-scale construction, it will be necessary to balance the desired resolution with an acceptable overall build rate. At 10 mm layer thickness, the differences between various nozzle designs and bead shaping approaches become readily apparent. The achievable surface finish is closely related to the process challenges discussed above in Sect. 2.1. In the case of the commonly used round extrusion nozzle, any pulsation or change in flowrate relative to the motion of the extruder tool center point (TCP) will change the bead width, resulting in a wavy edge

and also causing potential mechanical flaws in the structure. In the case of 3DP ECC, experiments have also shown that even with soft fibers such as PVA or PE, the fibers often penetrate the surface. Higher viscosity mixes, or those that are reaching the end of their “extrudability window”, often show buckling effects or tearing as they exit the nozzle. The goal of the proposed nozzle design is to reduce or eliminate these negative effects in printing with ECC, while striking a balance between resolution and printing efficiency.

3 Experimental Approach

3.1 3DP ECC Process Setup

The most current 3DCP setup used in this research was developed to maximize geometric control while addressing the challenges and opportunities of printing with ECC. The devised system is based on a 6-axis industrial robot with 2.8 m reach and 120 kg payload, mounted to a linear gantry (Fig. 1). In order to address the start/stop behavior, as well as to support dynamically variable material flowrates, the transport/placement system consists of a hopper mounted to a servo-driven peristaltic pump. This feeds a 4 m supply line connected to a custom-built servo-driven PC pump, mounted at the end of the robotic arm. A pressure transducer at the inlet of the PC pump provides feedback to the peristaltic pump in order to maintain constant inlet pressure, even as the PC pump starts/stops or varies flow. Due to the pulsation inherent in peristaltic pumps, and the deadtime between the pump and the transducer, the current setup causes a significant pressure swing, which can overcome the pressure-holding ability of the single-stage PC extruder and lead to excess material in the nozzle. By modifying the nozzle geometry to create an “open” area in the leading face, these material pulses can be buffered and shaped as they exit the nozzle.

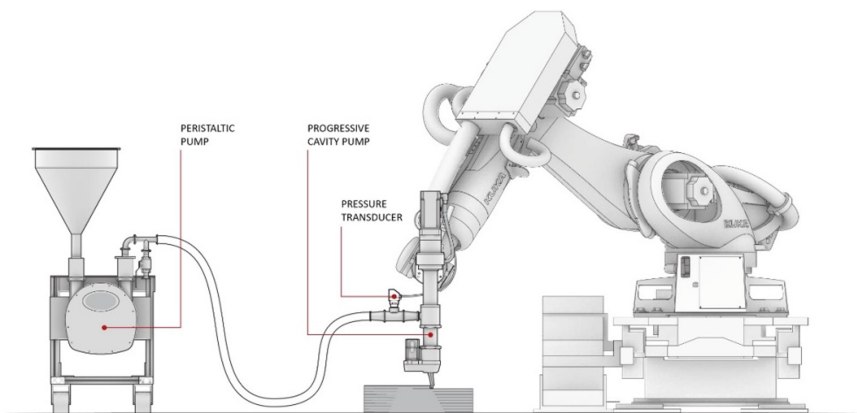


Fig. 1. 3DCP system consisting of supply pump and robotically positioned extrusion head.

Sizing of PC pumps is typically based on desired flow rates, and there are strict rpm limits due to the excessive stator wear and friction that results from higher speeds. With ECC mixes, the rotor/stator geometry requires a significantly larger pump to minimize the interaction or pinching that occurs between the fibers and the rotor/stator, even with soft fibers. This pinching leads to higher friction/rotor torque which could result in catastrophic damage to an otherwise properly sized pump. While friction can be reduced by lowering the mix viscosity, it is also observed that it is important to maintain a minimum mix viscosity to prevent bleeding.

3.2 Extrusion Bead Shaping

Previous research has adopted several approaches to controlling the shape of the extruded bead in 3DCP. The most basic approach utilizes a rectangular extrusion die opening that can be rotated around the axis of extrusion [9]. Other variations of this approach include the addition of one or more “side trowels” which shape the material as it exits the extrusion die [2]. In the following diagrams, u , v , w notation are as follows: with u designated as the direction of travel of the nozzle, v perpendicular to the bead direction but in plane with the bead, and w , perpendicular to the bead plane. As a starting point, the chosen cross-section of the extruded bead was rectangular, $10\text{ mm} \times 30\text{ mm}$ (w , v). The chosen shape of the extruded bead also has implications on overall component geometries that can be produced, as well as the surface finish, as shown in Fig. 2.

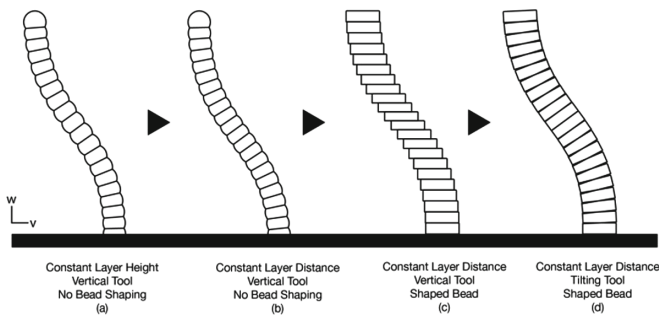


Fig. 2. Effect of tool orientation, nozzle shape, and toolpath strategy on wall cross-section in v - w plane. (left two sectional diagrams adapted from [8]).

As discussed in [8], constant height layers applied to a surface which has a curved cross-section will produce a layer interface with variable surface area as the vector distance between paths changes (further, the diagram does not account for the change in width that will occur if the extrusion rate is held constant) (Fig. 2a). By designing the toolpath using a constant tangential offset along the surface, a consistent layer interface surface area (per unit length) can be generated (Fig. 2b). The addition of bead shape control combined with a vertical tool produces a “corbelling” effect, similar to brick masonry, and results in a stepped surface with considerable roughness (Fig. 2c).

When combined with 5 DOF tilt, however, the cross-section can be produced with nearly identical interface contact area, thickness, and relatively low surface roughness (Fig. 2d).

When viewed from the u - w plane, there are several considerations, as shown in Fig. 3. In the simplest case, a rectangular die extrudes the material vertically, and it sharply transitions from the w to the u direction. Based on previous experience with round extrusion dies, this was expected to be problematic, particularly with ECC, where the high fiber content and internal friction leads to shape deformation as the bead bends. A second iteration includes a transition section in the trailing edge of the nozzle and was used to print the diagrid panel in Sect. 4.1. This version shifts the TCP of the nozzle to align with the axis of rotation in plan (assuming a steered nozzle). While shifting the trailing edge to align with the rotation axis is not strictly required, it simplifies path planning and simplifies the kinematics of the tool. The third iteration shows the addition of fixed “shaping blades” and was used to print the column in Sect. 4.1.

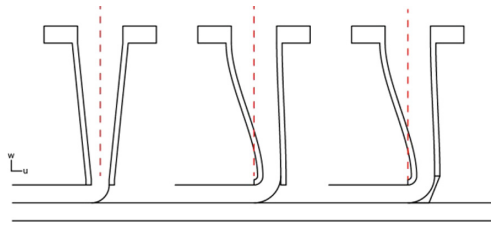


Fig. 3. Iterative design of extrusion nozzles, u - w plane.

In order to guide the rectangular die opening and/or the shaping blades, the extrusion tool requires an additional, sixth DOF, which keeps the nozzle tangent to the toolpath in the u direction. In the versions equipped with shaping blades, the specific shape of the blade creates additional constraints on the overall component geometry, particularly the minimum corner radius (Fig. 4). The geometric requirements also vary based on the projection length of the side blades. Figure 4 illustrates a nozzle with shaping blades extending beyond the previous layer to smooth the interface. However, fixed shaping blades prevent certain path topologies where lateral intersections between paths are desired; retractable blades are a potential solution to this problem.

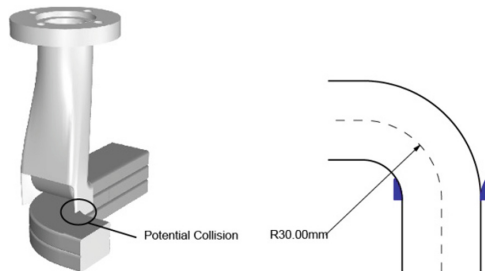


Fig. 4. Left, axonometric view of nozzle. Right, side blades (blue) and minimum centerline radius.

The final nozzle design parameters relate to the effect the cross-section has on the fiber alignment in the extruded bead. Ongoing work is underway to study and quantify the “wall effect” on the fiber alignment, and to understand how to best amplify this effect in future iterations of the nozzle. While prior work has addressed nozzle shaping strictly for its benefits to surface finish, this research suggests that especially in the case of ECC/SHCC, the design of the nozzle can have additional effects on the mechanical properties of the extruded bead as well as the behavior at the layer interface. This is an area which needs further study.

3.3 Integration of 6 DOF Nozzle Shaping into the 3DCP Workflow

Most 3D printing systems utilize only 3 degrees of freedom, and typical 3D CAD/CAM workflows treat extrusion as a fixed tool following a path at fixed speed, with no consideration for the shape of the bead. The 6-axis robotic manipulator offers the additional DOF necessary for complete control over the nozzle orientation, however, due to the size constraint of the PC pump and mounting/reach requirements shown in Fig. 1, an additional axis to control the nozzle rotation is attached to the end effector of the robot. This axis is integrated as an external axis, and the kinematics of the toolpath are solved using a custom-developed off-line programming (OLP) plugin for the Rhino3D modeling software [10]. The OLP approach allows the nozzle rotation and tool orientation to be synchronized kinematically, and output in standard machine instruction code. This research utilizes the Kuka Robotic Language (KRL), but the software can be easily adapted to other languages.

In addition to the nozzle rotation, the PC pump is also integrated as an external axis, in this case treated as a continuous (feed) axis. The rate of motion of this axis is computed in the OLP plugin and calibrated to the motion of the servo driven PC pump, yielding the potential for continuously variable extrusion rates (it can even be reversed to allow for retraction behaviors which are common in paste/filament extrusion). This opens the possibility of variable layer thicknesses, which are encoded into the machine instructions during the geometric analysis by the OLP software. These “virtual” axes are synchronized by the robot motion controller, and the positioning data is fed to a programmable logic controller (PLC), providing motion and process control for the entire 3DCP system.

4 Demonstration and Results

4.1 Evaluation of Nozzle Performance and Surface Finish

The nozzle design parameters described in Sect. 3.2 were tested using an iterative approach in order to determine their influence on the printing process and the resulting surface finish. As a proof of concept, two case studies were developed to demonstrate the constraints and benefits of the nozzle shaping system.

Diagrid Panel. The first case study is a façade panel with a doubly curved face, stiffened by a network of ribs (Fig. 5). As opposed to printing the panel in the vertical orientation, it was printed horizontally on a prepared mold, with the goal of improving

the surface finish of the doubly curved face. This design provided the additional opportunity to test the ability of the 3DCP process to aggregate layers horizontally for the face layer, as well as vertically for the stiffening ribs and flanges for the panel. Using the variable extrusion rate capabilities described in Sect. 3.3, the ribs are designed to have variable depth, but the same number of layers at every point in the w direction. This allows the doubly curved surface to resolve to a level datum at the upper layer. While demonstrated as a panel, this process presents numerous potential applications for the design of variable depth waffle slabs and non-rectilinear masonry units.

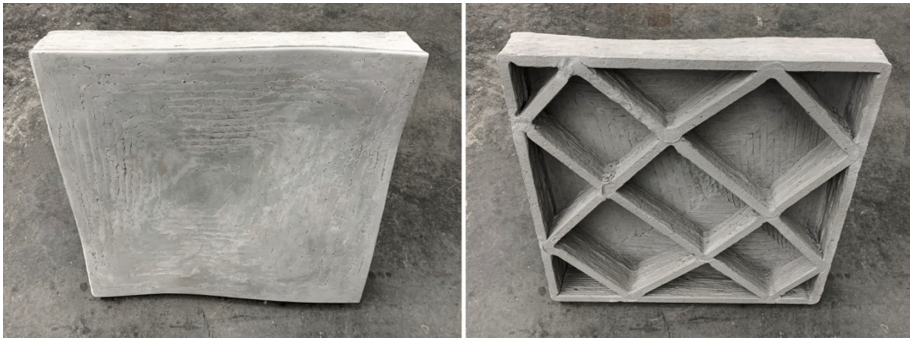


Fig. 5. (left) Double curved face printed on finished mold. (right) Stiffening Ribs and flanges printed with variable layer thickness.

In order to aggregate the layers horizontally, as well as allow the stiffeners to intersect and join at corners, the panel required the use of a nozzle without side blades. To achieve a seamless face coat on the mold, attention to the overlap of each successive bead was crucial, as well as an increase in the flowability of the mix. In this experiment, the print path has an offset equal to the nozzle width, and the flowrate is manually increased by 5%. After printing the face layer, the path continues directly into the stiffeners. The stiffeners also provided an opportunity to test the achievable surface finish without fully guiding the extruded bead. The results showed that the shear and bending stresses on the extruded bead cause a loss of fidelity as it makes the transition from the w to u direction in an unsupported way. Subsequent tests reveal that it is important to support the extruded bead for as long as possible to allow the deposited material to stabilize.

Bifurcating Column. The second case study was developed as a twisted, hollow column which bifurcates and recombines twice in elevation (Fig. 6). This study was developed to test the start/stop behavior of the system, to explore increased tilt steering with the 6 DOF system, and to test moderate overhanging of the geometry. Additionally, the corner radii were set at the minimum radius for the nozzle, which was designed with fixed side blades at 14 mm long.

The column print demonstrated that the nozzle shaping system could produce improved surface finishes relative to the nozzle without side blades. The performance

of the printing system is highly dependent on proper tuning of the flowrate. In the absence of a closed loop monitoring system, the flowrate required frequent adjustment. In part this is due to time-dependent material properties; at a given inlet pressure, as the mix viscosity begins to increase at the end of a batch, the flowrate decreases. In order to address this, the PLC motion controller, equipped with an operator override, allows adjustment of the flowrate as needed. Excessively low flowrates cause incomplete bead formation, whereas high flowrates cause excess material to pass below the side blades, producing small extensions at regular intervals which can be observed on the prototype. As such, future development in this area includes a sensing device which can evaluate the bead shape and adjust the flow rate automatically, building on approaches described in [11].

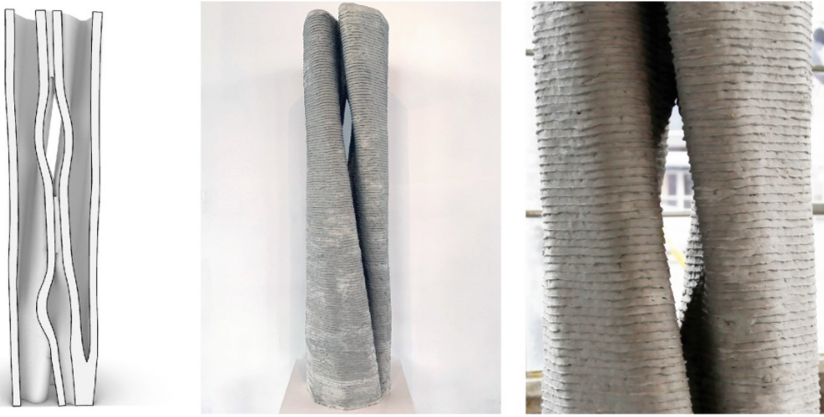


Fig. 6. (a) Section through the column. (b) Printed Result. (c) Close up of layer surface finish.

Material Effects. It was observed that ECC mixes can be adjusted to improve their shape-ability as they exit the nozzle. The shaping blades tend to stabilize the bead, possibly due to fiber alignment effect. This effect seems to be shear stress dependent (and thus is affected by the print velocity). This was particularly evident when the print speed was reduced in order to extend the time between batches. While the flowrate of the system is synchronized to the print velocity, the change in surface finish at low speeds suggests that a “stiction” effect can occur in the shaping nozzle. It is hypothesized that the thixotropic nature of the ECC mixes is contributing to the shaping effect, and that there is an optimum velocity which produces an ideal viscosity as the bead exits the nozzle. It also suggests that the mix design may have to be modified to offset shear-thinning as print speed increases.

5 Conclusion and Future Work

This research has explored the basic implementation of a nozzle shaping and 3DCP infrastructure which can support the deposition of ECC/SHCC materials with an improved surface finish compared to approaches which use a static printing nozzle. Further work will explore nozzle shapes and mechanisms which produce improved surface finishes across a wider range of component geometries, including those with self-intersecting paths. In addition to improving the surface finish of 3DCP building components, future work will focus on the development of a system which can support the deposition of materials with enhanced ductility and strength, with longer and/or higher volume fraction of fibers for reinforcement and stiffer matrices for higher buildability. Further study will also attempt to determine the impact of internal nozzle geometry on fiber alignment in ECC/SHCC mixes, as well as the effect on the shear thinning behavior at the deposition point in 3DCP. By taking an integrated approach to the design and manufacturing workflows used in 3DCP, the over-arching goal of this research is to develop a process which can produce highly refined, self-reinforcing building components with minimum material usage.

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Buildability of Geopolymer Concrete for 3D Printing with Microwave Heating

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Abstract. A novel application of microwave heating was investigated to attain on-demand setting of concrete for the improvement in buildability of 3D printable geopolymer concrete. An integrated microwave heating facility at the nozzle head was replicated using laboratory experiments to understand its effect on the structural build-up of printed filaments. Different microwave heating durations of 5, 10 and 20 s were studied, and the fresh and hardened properties were compared with control specimen (without microwaving). At optimised heating, the interlayer bond strength was found to be increased by 127% and 122% at 7 and 28 days respectively. Furthermore, structural recovery of material after extrusion that governs its buildability, showed a tremendous improvement at optimum heating period. Control specimens could only recover up to 32% of the initial viscosity, whereas addition of microwave heating for 10 s enhanced the viscosity recovery to more than 70%. Effect of microwave heating on cement based concrete 3D printing was also studied to assess the robustness of this technique. Outcomes from this study proposes a novel approach of applying microwave heating to construction 3D printing to achieve “set-on-demand” printable concrete. This study provides a starting point to develop new generation of print head to combat issues faced by current 3D printing practices.

Keywords: Construction 3D printing · Set-on-demand concrete · Geopolymer concrete · Microwave heating · Buildability

1 Introduction

Concrete printing or 3D concrete printing (3DCP) is often referred as large scale additive manufacturing process that precisely deposits sequential layers of specific volume to construct a facsimile of designed 3D model [1]. It is a form-work free construction technique with a nozzle and a positioning counterpart; fully controlled by the computer to extrude material at required printing coordinates [2]. 3D printing technology promises enhanced productivity and an eco-friendly construction method [2]. Meanwhile, ordinary Portland Cement (OPC), a major constituent of general concrete, is widely known for its negative impact to the environment [3]. Significant amount of research have been conducted to partially or fully replace cement with sustainable alternatives [4]. Alkaline activated binders or geopolymers are an

alternative to cement and they are reported to have enhanced properties [5, 6]. Rheology of a geopolymer, especially when produced using solid activator is controlled by two major steps [7].

1. Dissolution - In this process ions of alkali activators react with aluminosilicates (binders) to bring partially deprotonated aluminates and silicates (monomers) into the solution.
2. Polymerisation – Generated monomers undergo condensation reaction that results in a two- or three-dimensional microstructures linked via oxy-bridges (R-O-R). Each condensation process eliminates water, such that exhausted alkali during dissolution is not regenerated. These two steps occur repeatedly over time and oligomers of different monomeric units undergo polycondensation to form denser networks. It is well-known that the addition of heat accelerate these steps, which in turn, increases stiffening rate of geopolymer concrete [8]. Previous literatures [9–11] have reported microwave heating method results in rapid change in properties of geopolymer concrete in fresh and hardened state.

Issues related to insufficient strength of fresh concrete, corresponding to buildability, limits the application of 3D printing technique for large scale rapid prototyping [12]. Therefore, this study aims to analyse the application of microwave heating method to enhance building ability of geopolymer concrete. According to authors' best knowledge, this study is first in the area of concrete 3D printing and provides a strong foundation to conduct future investigations.

2 Materials and Methods

2.1 Binders and Activators

Fly ash (FA), a waste product from coal fired power plant and ground granulated blast furnace slag (GGBFS) were acquired from Independent Cement and Lime Pty Ltd. The oxide composition obtained using X-ray fluorescence spectroscopy (XRF) of FA confirms it to be a class F pozzolan ($(\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3) > 70$), whereas GGBS contained 39.09% of reactive CaO. The median diameter (D50) of fly ash and Slag were determined as 4.79 μm and 6.67 μm respectively from CILAS® laser particle size analyser. Sodium metasilicate in anhydrous form was used to activate GGBFS and fly ash in this study. It was procured from Redox Pty Ltd, Australia, with a composition of 51% Na₂O and 47% of SiO₂ and remaining 2% of bonded H₂O. Ordinary Portland cement (OPC) complying with AS 3972 was used for the preparation of OPC concrete 3D printing.

2.2 Aggregates and Fibre

Two grades of silica sand obtained from Sibelco Pty Ltd. and Metro Quarry Group respectively were used as aggregates to prepare printable geopolymer concrete. Silica sand denoted as “Coarse” has a specific gravity of 2.65; fineness modulus as 4.9; d₅₀ = 498.20 μm and d₉₀ = 583.39 μm . “Fine” sand with a relative density of 2.0–2.5

has a median particle size of 171.80 μm and 90% of the overall particles were smaller than 271.29 μm .

2.3 Material Formulation

Table 1 provides the mix design of printable one-part geopolymer used in this study. Raw materials were weighed accordingly and transferred into a Hobart mixer in a stepwise mixing schedule. Dry constituents including binder, sand and solid sodium metasilicate were uniformly mixed at 60RPM (lowest speed) for one minute. To maintain the workability of developed geopolymer for 3D printing, designed amount of mixing water was divided into two parts. These were added at different times of mixing process. First part of mixing water was added slowly while mixing was continued for 15 min. The mixing was paused intermediately to scrap the material from sides and bottom of the mixing bowl. This is followed by adding the remaining water and mixing was continued at medium speed 120 RPM for 2 min.

Table 1. Mix design of printable geopolymer used in this study.

Binder		Water/Binder		Sand/Binder		Activator
GGBS (in kg)	Fly Ash (in kg)	First part (in kg)	Second part (in kg)	Coarse (in kg)	Fine (in kg)	Na-Silicate (in kg)
0.5	0.5	0.30	0.05	1	0.5	0.01

3 Experimental Program

3.1 Interlayer Bond Strength

A lab-scale 3D printer with a rectangular nozzle of 25 mm (L) $\times$ 15 mm (W) was used to print a 250 mm long double layered structure. Nozzle was designed to reduce the impact of extrusion pressure on the interlocking of printed layers. It was achieved by optimising the angle between nozzle opening and printing direction. Furthermore, the nozzle was lifted to 17.5 mm after printing first layer to ensure minimal physical interlocking. This method of printing was used for control sample, whereas to investigate the effect of microwave heating on interlayer bond strength, individual printed layers were heated inside a microwave oven operating at 2.45 GHz and 1200 wattage for 5, 10 and 20 s before stacking. 3 rectangular prisms with dimensions of 50 mm (L) $\times$ 25 mm (W) $\times$ 30 mm (H) were extracted from the printed structure and cured at 25 $^{\circ}\text{C}$ and 50% humidity for 7 and 28 days. The interlayer bond strength was determined by evaluating the splitting tensile strength of double layer specimen as shown in Fig. 1. A 4 mm notch on both sides of the specimen were created to hold the clamps and ensure failure occurs at the interlayer. The clamps were connected to a universal testing machine to pull the specimen at 0.5 mm/min until failure.

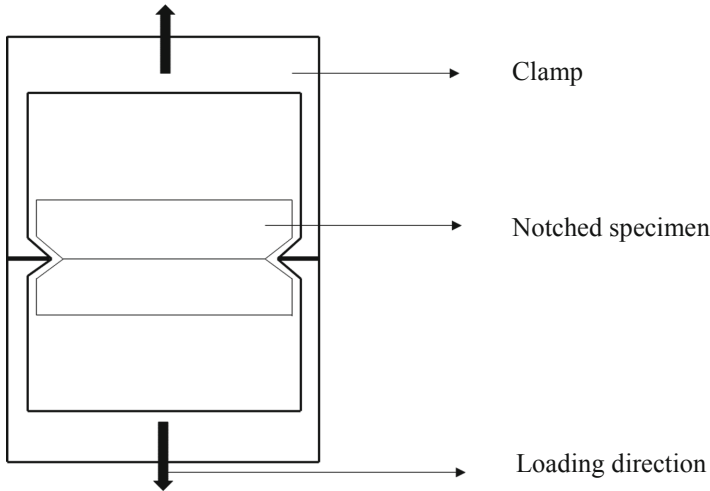


Fig. 1. Schematic representation of experimental setup used to determine bond strength

3.2 Structural Recovery

Rheometer (Viskomat XL) developed by Schleibinger Testing Systems was used to determine the structural recovery of developed one-part geopolymer concrete. 6-blade vane probe with blade dimensions of 69 mm height and 34.5 mm radius was used for the assessment. Fresh geopolymer mix (immediately after mixing) was poured into the rheometer cup and a three-stage shearing protocol (Fig. 2) was followed to simulate the extrusion process of the lab scale 3D printer. After stage 2 (shearing at 30 RPM), the material was taken out of the cup and was heated inside the microwave oven for 10 s, whereas for control, the material was kept idle for the same duration. Then, the material was transferred to the rheometer and a similar shearing was performed as that of stage 1 to evaluate structural recovery of the printable geopolymer composite.

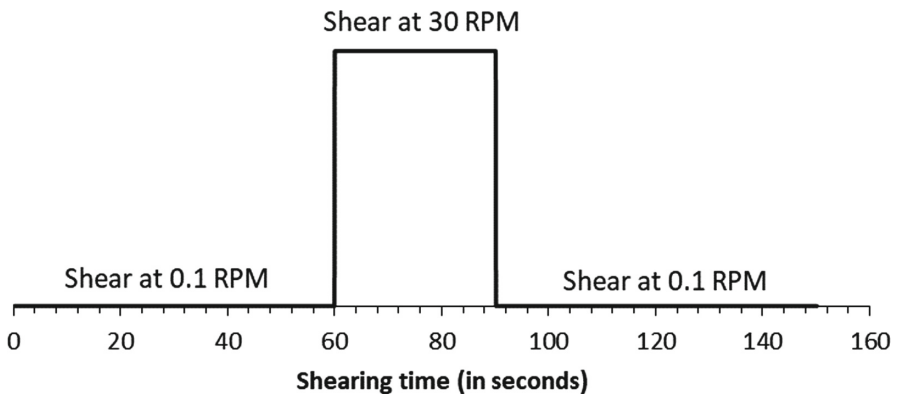


Fig. 2. Shearing protocol used to determine structural recovery after extrusion.

3.3 Microwave Heating of Cement and Geopolymer

Effect of microwave heating on cementitious and geopolymer concrete composites were tested to determine the robustness of this technique. Mix design as discussed in Table 1 was used for this assessment, where total binder (GGBS+FA) was replaced with cement to compare microwave heating of OPC concrete with geopolymer. A temperature profile of a cylindrical container filled with concrete was determined at various heating period of 0, 5, 10 and 20 s. Surface temperature right after heating was recorded using an infra-red thermometer, whereas bulk temperature inside the concrete (at locations marked in Fig. 3) was recorded using K-type thermocouples.

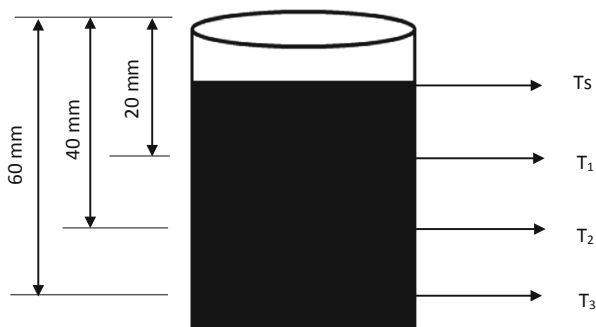


Fig. 3. Points of temperature measurement for microwave heated concrete

4 Results and Discussion

4.1 Bond Strength

Figure 4 shows the failure specimens captured after testing for 7-days. Here, one could notice that, cracks in some specimens propagated through the filaments under tensile load instead of separation at the inter-layer. These specimens were discarded from the analysis. Similar approach was used for 28-days testing as well. Figure 5 presents the 7-days and 28-days tensile bond strength of two-layered printed elements. Regardless of the curing age, the bond strength increased with increase in duration of microwave heating. At 7 days, samples with heating duration of 5 and 10 s exhibited interlayer bond strength of 0.52 MPa and 0.79 MPa respectively, which is equivalent to 51% and 127% increment from samples without any treatment. Similarly, at 28 days of concrete maturity, printed samples corresponding to 5 and 10 s of microwave heating exhibited a strength of 0.82 MPa and 1.53 MPa respectively that corresponds to an increment of 19% and 122% from the control respectively. This could possibly be due to acceleration in geo-polymerisation reaction by increased bulk and surface temperatures as a result of microwave heating. However, prolonged heating ($T = 20$ s) reduced the bond strength significantly. At 7 days, sample prepared by stacking microwave heated layers for 20 s exhibited bond strength of 0.20 MPa whereas at 28 days, the strength was determined to be 0.42 MPa. This corresponds to a reduction of 41% and 38%

respectively to the control specimen. While kinetics behind geo-polymerisation depend on system temperature, its relationship towards reactant concentration is equally sensitive. Most likely, at 20 s of heating, water that acts as a medium for dissolution of reactive monomers is lost due to rapid evaporation. In addition to that, filaments after prolonged heating loses its malleability that is required for effective overlapping of two stacked layers. This corresponds to minimised contact area between the layers that eventually causes weak bond strength between layers.



Fig. 4. Specimens after testing for 7-days bond strength

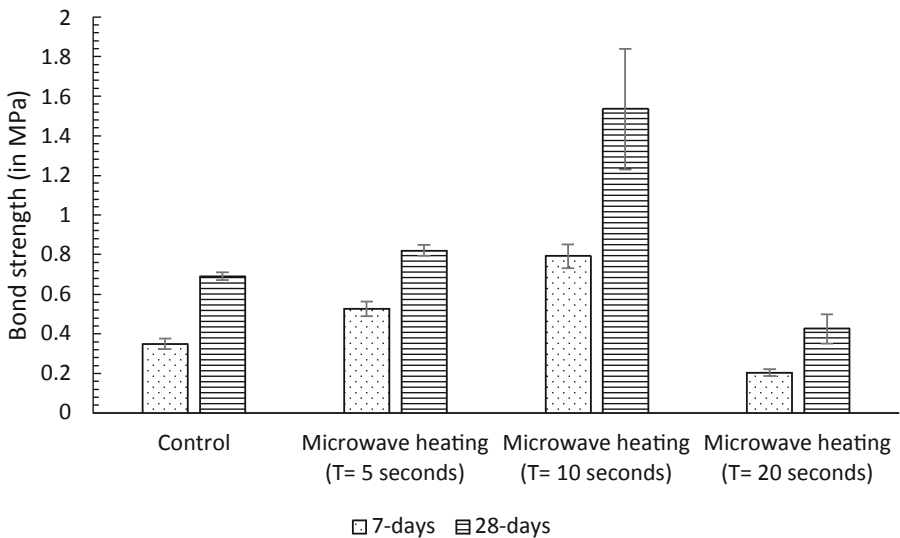


Fig. 5. Effect of heating duration on 7 and 28-days interlayer bond strength.

4.2 Viscosity Recovery

Printable material is thixotropic in nature. This means, under continuous shearing action, the mix loses its viscosity, whereas at rest, it gains back its initial flow properties due to reversible flocculation. Figure 6 compares the extent of viscosity recovery of microwave heated fresh geopolymer pastes with control specimen. This assessment interprets rheological behaviour of material at three stages of extrusion process. First stage corresponds to material before feeding into the extruder, which is followed by stage two, that reflects material during extrusion. Stage 3 simulates the condition of printed layer after deposition. Ideally, dynamic flow properties (viscosity) after shearing at stage two should be equal to that observed during the first stage. However, geopolymer composite used in this study (without microwave heating) could only recover up to 32% of its initial viscosity as shown in Fig. 6. This is due to high zeta potential of geopolymer particles that corresponds to low flocculation after shearing. Elaborate discussion on zeta potential and respective agglomeration of cement and geopolymer particles is done elsewhere [13]. As 10 s microwave heating resulted in maximum interlayer bond strength, its effect on viscosity recovery was determined and shown in Fig. 6. At this heating duration, the material recovered up to 73% of its initial viscosity that corresponds to more than 100% higher viscosity recovery than control. Rheological behaviour of geopolymer is governed by flow properties of activator in the early stage and later by geo polymerisation reaction. Since, solid phase activators are used to produce geopolymer in this study, the extent of dissolution would govern its impact on concrete's rheology. Therefore, accelerating geo-polymerisation by microwave heating is considered to be the primary reason for such remarkable recovery.

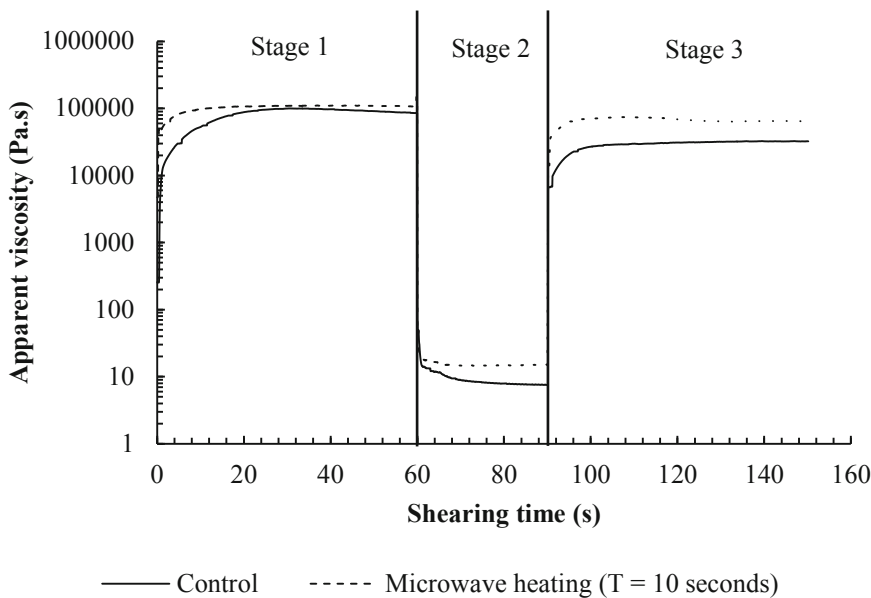


Fig. 6. Effect of microwave heating on viscosity recovery.

4.3 Temperature Profile

Table 2 reports the temperature profile of geopolymer and OPC concrete that were heated using microwave induction. Regardless of the concrete type, temperature increased with increasing heating duration. Temperature observed at points T_1 and T_2 were higher than that measured at the surface. This due to the uniform heating of concrete by vibration of di-electric molecules, that results in high temperature at the bulk and lower at the surface, which experiences convective cooling. Rate of cement hydration and polymerisation reaction are governed by system temperature. Moreover, to enhance buildability, printed layer should exhibit fast stiffening rate, meanwhile also be sufficiently malleable to have an effective interlayer contact. Therefore, at controlled heating duration and radiation frequency, one could produce printed layers with hard core and soft surface for enhanced buildability with this method. Figure 7 compares the average temperature of cement and geopolymer based concrete at different microwaving duration. Control ($T = 0$) for geopolymer concrete is warmer than OPC based concrete, due to the exothermic dissolution of anhydrous sodium silicate activator. Moreover, the average temperature of geopolymer concrete was observed to be higher than OPC concrete at all heating durations. It is most likely due to higher concentration of dielectric ions (from activator) in geopolymer binder than in cement. Difference in temperature between geopolymer and OPC concrete reduces with increase in the heating duration. At 5, 10 and 20 s of heating, geopolymer was 13 °C, 11.45 °C and 7.2 °C warmer than OPC concrete. Further research is required on how the temperature of printed filaments affect the malleability and interlayer bond strength. Nevertheless, it could be concluded from the results that microwaving is promising solution to attain rapid heating followed by stiffening for both geopolymer and OPC based concrete.

Table 2. Temperature profile of microwave heated concrete

Concrete type	Heating duration	T_s	T_1	T_2	T_3
	in seconds	in °C	in °C	in °C	in °C
Cement based	0	21.3	21.4	21.3	21.5
	5	32.2	37.6	41.2	34.5
	10	53.1	62.7	63.1	52.1
	20	69.6	73.5	71.7	73
Geopolymer based	0	27.3	27.5	27	27.1
	5	45	53.1	49.2	50.2
	10	67.6	61.8	79.1	68.3
	20	77.4	75.8	85.3	78.2

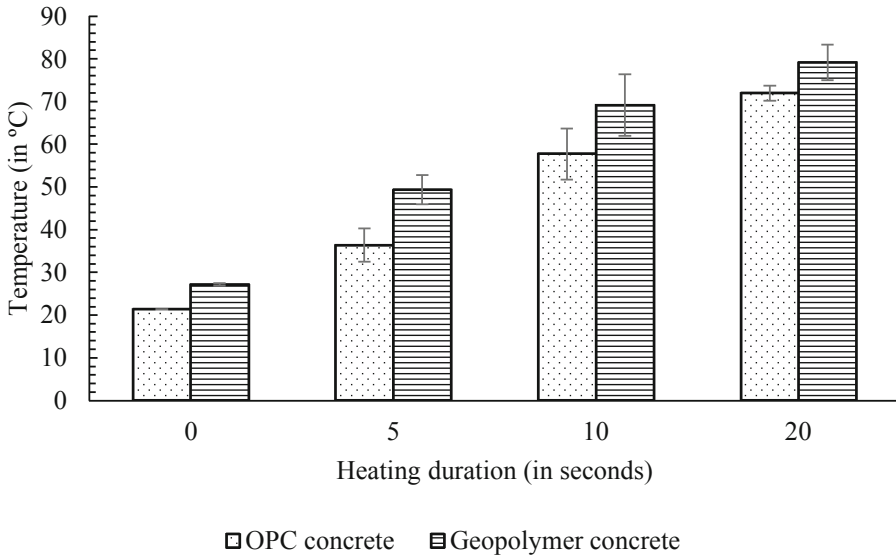


Fig. 7. Effect of microwaving duration on average temperature of concrete.

5 Conclusion

Results from this study infers microwave heating of geopolymer concrete before extrusion increases interlayer adhesion of the printed elements. At optimised heating duration ($T = 10$ s), interlayer bond strength at 7 and 28-days of maturity showed a remarkable improvement of around 122% and 127% from control respectively. However, prolonged heating ($T = 20$ s) showed negative impact on the bond strength. It is possibly due to low malleability of printed layers at this heating duration. In addition, microwave heating enhances the viscosity recovery of geopolymer concrete that could only recover up to 32% without any thermal treatment (control). The microwave heating can also be applied to OPC based concrete 3D printing as it exhibits similar behaviour to geopolymer. With increased interlayer adhesion and structural recovery, microwave heating highlights itself as a promising technology to combat the issues related to buildability in current 3D construction printing practices.

Acknowledgement. The authors acknowledge Swinburne University of Technology, Australian Research Council and Industrial Manufacturing CRC for supporting the project through SUPRA scholarship, Discovery Early Career Researcher Award of DE190100646, and funded project of “Manufacture of Next Generation Speedpanel” respectively.

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High-Resolution Additive Formwork for Building-Scale Concrete Panels

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Abstract. The paper discusses the technical developments in using 3D printed reusable formworks for the production of high-resolution building-scale concrete panels. The research looks at innovation in the production of concrete elements and extends current design possibilities with economically viable moulds. The relation occurring between the presented manufacturing technique, namely Fused Deposition Modelling 3D printing, and diverse designed morphologies is studied, assessing limits and opportunities of the application through an experimental setup. The first experiment analyzes a set of thermoplastics to identify suitable materials for the specific application in concrete formworks. The second experiment tests a consistent workflow for the digital modelling and optimization, 3D printing and concrete casting of a series of unique panels that challenge the formal possibilities of concrete manufacturing. The outcomes are analyzed quantitatively and qualitatively, in terms of formal possibilities offered by the approach, material behaviour, ease of manufacturing, and achievable precision, discussed for relevant applications in architectural envelopes.

Keywords: 3D printing · Additive Formwork · Fused Deposition Modelling · UHPFRC · Informed texture

1 Introduction

Formwork production for concrete elements, being them precast or cast-in-place, is impacting for about half of the overall cost and time of the construction work, increasing even more when dealing with non-standard architectural elements [1, 2]. In recent years, the necessity for shifting from the conventional formwork led to recent explorations in Additive Formworking, with a special focus on Fused Deposition Modelling (FDM) 3D Printing [3–5]. This approach is an affordable solution for non-standard geometries, offering the opportunity of adding a new set of functional features to concrete elements. This paper specifically investigates the design of *informed textures* enabled by the use of Additive FDM Formwork.

Surface textures in concrete architecture have traditionally been a passive result of the manufacturing processes, as the marks impressed by wood formwork boards. In history, the external surface of the concrete was rarely investigated and designed actively [6] before recent work based on digital fabrication [7, 8]. In this paper, we

describe the use of 3D printing to realize high-resolution concrete panels with informed textures that can be programmed in the digital modelling environment.

Building upon previous experiments and findings [9, 10], we aim at studying the factors and implications of utilizing FDM technology to produce such concrete panels at the building scale, posing particular attention to the relationship between geometry and fabrication. Every manufacturing process has indeed inherent limitations that need to be addressed in the design phase, and that often defines features, and ultimately a design style [11]. 3D printing overcomes most of the typical constraints, and in particular the need for standardization [12] - but still carries certain material and geometric features that have to be taken into account. The presented work attempts at describing the design and fabrication space useful for designing concrete panels produced through Additive FDM Formwork manufacturing (Fig. 1).



Fig. 1. Detail of a high-resolution concrete panel realized through Additive FDM Formwork in the design experiment presented in the paper.

2 Methodology

The paper is fundamentally describing two interlinked experiments. The former is a material experiment to select an appropriate thermopolymer for the application as 3D printed concrete formwork, through a quantitative and qualitative assessment of custom specimens at building scale. The latter is a design-make experiment focusing on the morphological possibilities offered by the fabrication technique, where eight concrete panels are designed with computational tools and produced, providing a multi-parameter evaluation of the fabrication process and the accuracy of the final product.

2.1 Material Experiment: Assessment of Thermoplastics for Additive FDM Formwork

The application of thermoplastics as reusable formwork for concrete requires different characteristics: mechanical strength to withstand the hydrostatic pressure; low surface adhesion to guarantee an easy demoulding; durability to allow multiple pouring cycles. Different plastics can offer such characteristics, however, their behaviour can vary considerably and affect the geometrical characteristics of the final object. In this first experiment, we evaluated four commonly available thermoplastics for 3D Printing [13]: Polylactic Acid (PLA), Acrylonitrile butadiene styrene (ABS), Polypropylene (PP) and a Glycol Modified version of Polyethylene Terephthalate (PET-G). The experiment consists of 3D printing from pellets a custom specimen that resembles a simple formwork, based on an open parallelepiped of dimensions $500 \times 500 \times 40$ mm with a wall thickness of 4 mm and a layer height of 1 mm. Given the different material characteristics [14, 15], for the PLA print was used a typical heated bed, while the other materials required a custom-made perforated steel plate to improve the mechanical adhesion to the base. Different iterations were necessary for a successful print of the specimens in ABS and PP. During the manufacturing process, the chamber temperature and the cooling rate have been monitored to gain an understanding of the warpage and deformation (Fig. 2).

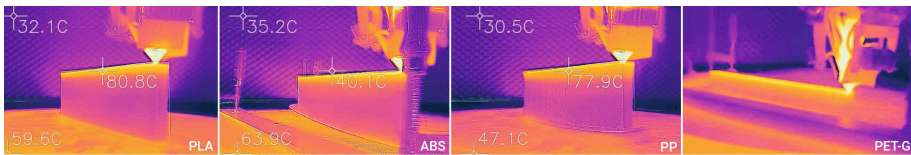


Fig. 2. Thermal Camera images showing the different cooling rate of the four tested materials.

The printed specimens have then been digitized through 3D scanning. From a comparison between the 3D scanned specimens point clouds and the digital models can be observed a different behaviour in the four materials (Fig. 3). All the specimens present a non-constant deformation on the XZ faces whereas a nearly linear deviation along the YZ sides with the only instabilities in the first layers caused by the warpage of the materials. PLA and PETG show relatively small deviations: respectively 1.9 and 2.4 mm in the Y direction, and a constant shrinkage of around 1.5 mm in the X-direction. ABS and PP have large inward and outward deformation areas which can be observed along the Y-axis, reaching 13.8 mm and 29.2 mm respectively; in the X vector, both ABS and PP are highly deformed in the first layers due to the high warping stress, while maintaining a constant dimensional shrinkage of 2.9 and 4.6 mm in the remainder of their surfaces. In the Z dimension, PLA resulted shorter for around 1 mm, ABS and PET-G around 2.5 mm, whereas PP total height was reduced by 7 mm. The largest deformations occur in the Y-direction, on the wider faces (XZ) of the specimens, reaching values as high as 231% of the original 40 mm dimension in PP (Table 1).

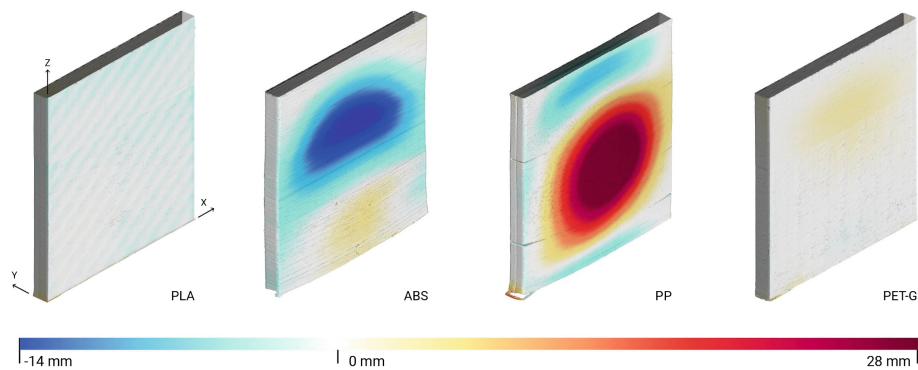


Fig. 3. CAD-comparison of the four 500 × 500 × 40 mm test specimens with the digital model. From left to right: PLA, ABS, PP, PET-G.

Table 1. Deviations illustrated through the X, Y and Z dimensions of the bounding box of the scanned specimens

	Dim.X (500 mm)		Dim.Y (40 mm)		Dim.Z (500 mm)	
PLA	498.2	(99.6%)	40.9	(102%)	499.1	(99.8%)
ABS	504.1	(100.8%)	54.3	(135%)	497.2	(99.4%)
PP	506.3	(101.2%)	92.7	(231%)	493.0	(98.6%)
PET-G	498.8	(98.7%)	43.7	(109%)	497.6	(99.5%)

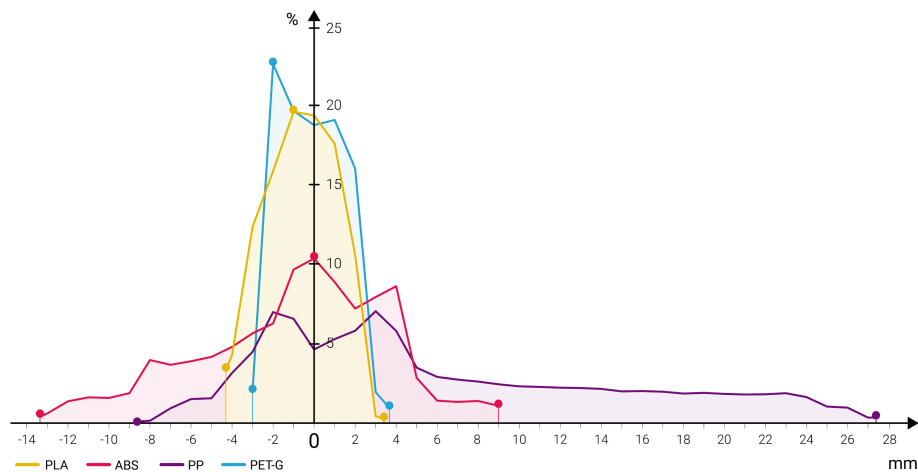


Fig. 4. Percentage occurrence of deviation from the digital model of the four tested materials.

A study on the occurrence of deviation in the four specimens highlights the lower and more stable deformation pattern of PLA and PET-G compared to ABS and PP (Fig. 4). Overall, PLA and PET-G demonstrated the highest precision, while ABS and PP showed unpredictable behaviour, higher deviations and sometimes cracks due to the warping tensions after being released from the base plate. Their regular deviation happened on the YZ due to the shrinking of the material, which can be taken into account and compensated during the preparation of the printing files. Among the tested polymers PLA was selected as suitable for further experiments, also considering that it is biodegradable and non-toxic [16].

2.2 Design-Make Experiment: High-Resolution Building Façade Panels

After assessing the properties of different thermoplastics for 3D Printing, the paper investigates the formal opportunities and limitations of using FDM to produce formworks for building-scale concrete panels. Despite a number of research experiments employing FDM 3D printed formworks, the literature does not present a comprehensive study of the geometric features and precision enabled with this approach. This experiment analyzes the relation between geometry and fabrication with a series of designs that explore diverse morphological/geometrical features, starting again with a standard module of 500×500 mm. The experiment challenges the fabrication of unique concrete panels, where a high-resolution design impossible with other fabrication techniques is achieved [17]. Each panel explores variable conditions of sectional thickness, Gaussian curvature, curvature variation, pattern scale and density, printing and demoulding angles, as well as geometrical or topological discontinuities such as sharp edges and holes (Fig. 5). Printing angle is defined as the angle between the printing direction and the vertical axis; demoulding angle is that occurring between the Y direction and the normal to the surface at each point.

The digital models were then sliced into horizontal layers and translated into a 3D printing .gcode using a custom-developed script within the Grasshopper environment, part of a seamless workflow which integrates a printability check. The formworks were joined in pairs to obtain a stable geometry during printing, with a continuous toolpath to enhance the fabrication speed and surface finishing. Integrated into the slicing process, a set of details were added: a brim surface was embedded at the base of each form for optimal adhesion during the print, and two lateral surfaces for later connection to a support frame during concrete pouring. The specimens were manufactured with an industrial FDM printer using PLA pellets obtained from shredded waste from industrial production (Fig. 6). Printing at a temperature of 195°C with a continuous toolpath, the 834 layers of 0.6 mm height of the 500×500 mm formworks were printed with an average time of 4,5 h/panel, for an overall printing time of 35 h and 30 min. The eight formworks have a thickness of around 4.5 mm for a weight that varies between 1.95 and 2.12 kg.

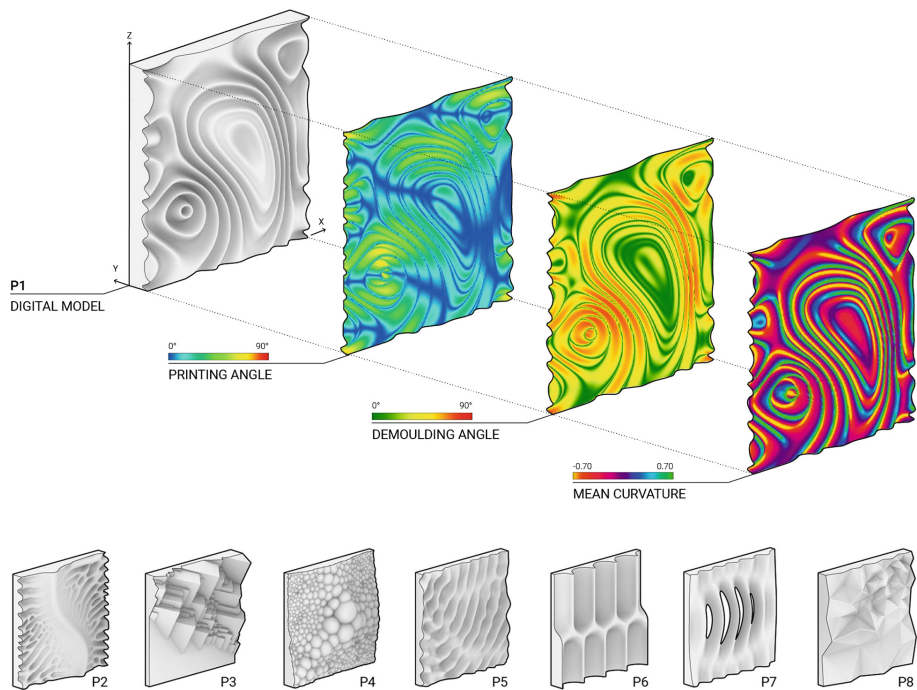


Fig. 5. Geometric analysis of the digital tiles: printing and demoulding angles, mean curvature.



Fig. 6. Close-up of the 3D Printing process with PLA from production waste.

2.3 Fabrication of Concrete Elements

After printing, the paired moulds were separated, laid horizontally, and placed into a standard wooden frame (Fig. 7). Oil was applied to the mould as a release agent, before pouring an Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) mix with 12 mm steel fibres - specifically a Compact Reinforced Composite (CRC) with a design characteristic compressive strength of 110 MPa measured on 150 mm × 300 mm cylinders [18]. The used CRC matrix is self-compacting, has a high binder content, a large content of micro silica and water/binder ratios of 0.16, satisfying the rheological requirements for the concrete to fill highly detailed geometries [19]. After 72 h of curing, the plastic formworks were detached from the concrete panels. For most of the panels, the demoulding was easy and required only pulling the formwork. However, P1, P3, and P4 presented challenges in this process: in particular, P3 required the use of heating tools to extract the panel, due to a combination of sharp edges and steep demoulding angles.



Fig. 7. The casting process of two adjacent panels positioned in the modular wooden frames.

2.4 Scanning and Verification

By means of optical structured light 3D scanning, both the 3D printed moulds and the casted concrete panels were digitized and compared between themselves and with the original 3D model. By using Triple Scan Technology, the projector is used as a calibrated unit in the measurement. In this way, three different methods are used for capturing data during the scanning process, as both cameras and projector are calibrated and used to calculate the coordinates [20]. The scanner generated detail-adaptive point clouds in the range of 1.5 million to 2 millions points, with a nominal accuracy between 0.06 and 0.12 mm. Detailed meshes exported as .stl files were also generated. The point clouds were then imported and analyzed in Grasshopper through Volvox [21], where deviations were outlined for each of the formworks and the concrete panels,

taking into consideration a 2,25 mm offset from the .gcode toolpath, as a compensation for the measured layer thickness.

3 Results and Discussion

The presented experiments demonstrate successful results in manufacturing high-resolution concrete panels with complex and variable geometry, through the use of Additive FDM Formwork (Fig. 8). Design features down to the scale of 3 mm were correctly prototyped with minimal deviations and nearly imperceptible defects.

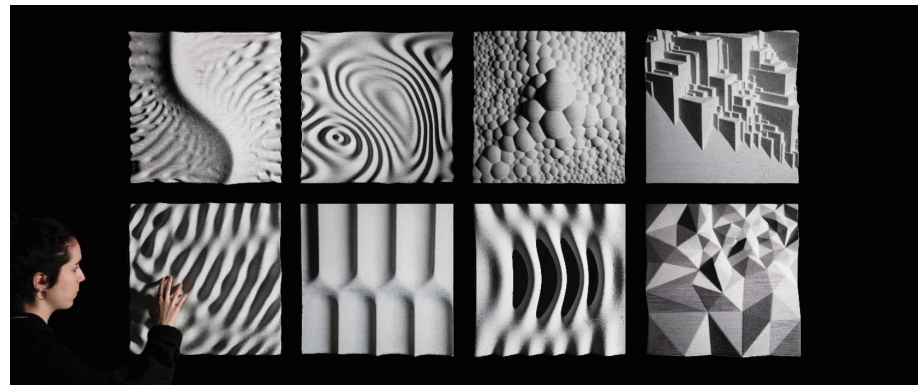


Fig. 8. The eight concrete panels challenging the formal possibilities offered by 3D printing.

From the scanning, a total average deviation of the formworks of 1.07 mm is observed (Table 2). Most formworks deform in the X direction towards the centre as a consequence of PLA shrinkage [22]. In the concrete panels, P4 and P7 present deviations up to 8 mm but an overall average deviation of the concrete of 1.52 mm; P3 and P8 present deformations in the barycenter, possibly due to the weight of concrete (Fig. 9). Printing angles have no direct influence on deviations. However, P3 and P8 present different finishing and difficult demoulding. Generally, we can observe that a combination of high printing angles, steep demoulding angles and curvature complicates the demoulding, and impacts partially on the manufacturing quality.

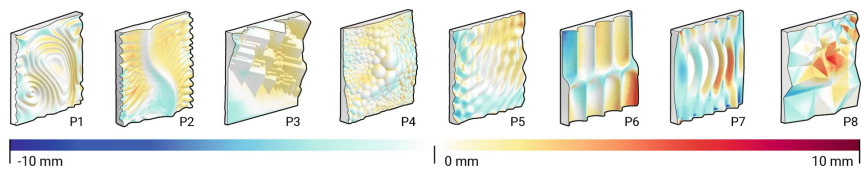


Fig. 9. Deviation analysis: the 3D scans of the concrete panels compared to the digital model.

Table 2. Deviations between the digital model, scans of the formworks and the concrete panels.

Panel	Formwork average deviation		Concrete average deviation		Deviation domain
	mm	%	mm	%	mm
1	0.68	0.13	0.77	0.15	−4.00 to 3.10
2	1.84	0.36	2.11	0.42	−5.69 to 4.03
3	1.11	0.22	1.45	0.29	−2.41 to 5.03
4	1.01	0.20	1.12	0.22	−4.00 to 8.22
5	0.98	0.19	1.09	0.21	−4.61 to 4.85
6	1.03	0.20	1.62	0.32	−4.34 to 7.02
7	1.05	0.21	2.29	0.45	−8.89 to 6.11
8	0.91	0.18	1.77	0.35	−6.21 to 7.23

4 Conclusions

Formwork manufacturing for non-standard geometries is a relevant challenge in the construction industry, and this work demonstrates the use of FDM formwork as a viable method. Perspective applications include the design of building envelopes, as well as concrete slabs and columns with complex design features. Future work will improve precision through the use of simulation to predict and correct deformations; the printing of reinforcing elements to prevent deformations, favour the demoulding and withstand the hydrostatic pressure with larger construction elements.

Acknowledgements. This work was carried out at the CREATE Lab at the University of Southern Denmark - Section of Civil and Architectural Engineering. The authors wish to thank David Wendel Jokszies for the assistance, Hi-Con for in-kind support of concrete material, and Ass. Prof. Knud Bjørnholt for the 3D Scanning at the SDU Prototyping Lab.

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Architectural Applications and Workflows for Additive Fabrication with Concrete

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Abstract. Although the fundamental scientific understanding of the relations between design, material, process, and product in additive manufacturing with concrete is already being explored, the relevance of this construction method for architecture and building is still limited. Additive manufacturing holds the promise that any computer-generated geometry can be produced. However, especially FDM-based processes are currently limited by geometrical and material-related restrictions. This study reflects on the digital workflow between architectural design, the geometry, and numeric data produced, construction processes and the material parameters in the research project “BauProAddi” on additive manufacturing with concrete. The purpose of the research is to integrate the knowledge of material and process specialists and requirements of the building industry at an early stage of the design process in a workflow for on-site additive manufacturing.

Keywords: Additive manufacturing · Digital workflow

1 Introduction – Current State of AM in Architectural Design and Construction

The Architecture, Engineering and Construction (AEC) industries are facing a huge productivity problem. While other industries such as retail or agriculture have been able to increase their productivity by up to 1500%, AEC has seen virtually no productivity increase [1]. In addition, the AEC industry is confronted with a growing shortage of well-trained personnel suitable for the physical demands of construction sites due to current demographic developments. Whereas the manufacturing industries have already adopted an advanced integration between the physical and the digital world [2], including other technological advancements such as Internet of Things, Cloud Computing, and Big Data Analysis to increase productivity, this is rarely the case in the AEC industry yet. With the advent of new digital design and production methods, the construction industry has increasing access to enormous datasets that could impose severe implications in the building industry. However, these are rarely integrated. For many years, researchers have agreed that efficient integration and coordination of design, construction, and management data can potentially benefit the overall performance of the building industry [3]. Further milestones to be achieved on the way to

Industry 4.0 standards in AEC include the introduction of new materials as well as the automated production of individual components and later complete structures. Since the mid-nineties, universities and companies have started to attempt to apply additive manufacturing (AM) on a building scale and several methods of AM with concrete are currently being researched [4] (Wangler et al.). Processes of the category of material extrusion so far can be realized with the least effort in technology and with a lower quantity of printing material. Hence, the recent focus of research is on material extrusion. Contour Crafting (CC) is one project of this type and was published already in 1998 by Khoshnevis et al. [5]. Another extrusion-based process without trowel was published under the name Concrete Printing in 2009 by Loughborough University [6].

2 Challenges on the Way to an Automated Construction Site

The first applications of AM show what can be achieved with this new technology in the future and how it can prepare the construction industry for the challenges of the 21st century. AM can support the design of more efficient buildings that better respond to challenges such as resource scarcity and rising construction costs, as well as to specific design requirements such as contextual information or client wishes. Previously “impossible to produce” building elements can increase performance while lowering weight and add new pathways for expressive architectural design. To achieve a greater impact of AM, it has to enable design freedom in combination with more functions. A reinterpretation of conventional building elements towards functionally integrated components is needed, considering the limitations and possibilities of the additive process and providing useful additions to existing building systems. At the same time, AM also poses numerous challenges for the design of material, processes and buildings. Design for additive manufacturing must be carried out according to the processing restrictions, e.g., layer thickness, nozzle dimensions, etc. and the functional properties of the final building element, e.g., mechanical strength, thermal conductivity, etc. The constraints need to be considered synergistically at three different design levels: the level of the material design, the design manufacturing process, and the design of the building part and functionality [7]. These challenges are briefly described in the following sections.

2.1 Material Design

In contrast to conventional concrete casting in formworks, the 3D printing of cement-based materials completely dispenses with formwork. Thus, both the formwork components and the personnel costs incurred in erecting and removing the formwork are saved. In direct consequence of these advantages, very high demands are placed on the printed material itself [8]. According to Lim et al. the pumpability, extrudability, the dimensional stability of a printed layer under the load of the overlying layers, and the open time of the material have been defined as the four parameters that must be

precisely set when developing a printable, cement-based material [6]. In particular, the parameters of pumpability and printability, i.e., the flowability of the material within the printer, are opposed to the high dimensional stability of the material after extrusion. For the material to be pumped well, it must be optimally matched to the printer used and its material handling system. If the open time is significantly less than the time it takes for the printer to extrude a complete layer of the body to be printed, there is a risk of “cold joints” (poor adhesion between layers) [9]. Building designs must be adapted to the material properties and be subdivided into printable compartments.

2.2 Manufacturing Process

When manufacturing a 3D printed concrete component, successive layers are deposited by a manufacturing machine to build a complete structure. Machine paths must be planned according to the kinematics of the production machine to fabricate the component in a reasonable period. The geometry of the paths should be adapted to both the material properties and the manufacturing process. When generating paths, different approaches can be chosen that have different advantages and disadvantages. Using a 3D to 2D slicing software, a three-dimensional digital model of an object is split into flat, thin layers of constant thickness that are stacked one on top of the other. Each layer then consists of a contour line, as well as a filling pattern of so-called space-filling curves (Peano curve, Hilbert curve, etc.); the filling density can be adapted to given requirements. This method is straightforward to automate processes and is well established for AM and 3D plastic or metal-based printing processes.

2.3 Robotic Fabrication

The exponential increase in productivity in manufacturing industries over the past decade is partly due to the extended use of industrial robots. Research projects are currently following a variety of approaches to introduce robotics in architecture. Robot programming tools have been developed that provide a quick and easy way to control robots from architectural CAAD environments. These controllers, such as HAL® [10] and KUKAPRC® [11], are tools to program motion paths within Rhinoceros, a common 3D-modelling application available to the design and engineering professions and have significantly pushed the development of construction robotics. However, McGee et al. describe that the complex world of construction remains a significant challenge for a broader application. Whereas in manufacturing, robots and manufactured products have static positions and fixed movement trajectories, construction sites are constantly evolving, and are changing shape and form in response to construction tasks. They rely on human improvisation in response to in-situ conditions [12]. A common approach is therefore that robotic additive manufacturing remains a pre-fabrication process in which components are manufactured in a controlled environment and then transported to the construction site.

2.4 Building Part Geometry and Functionality

The generation of geometries for additive manufacturing must meet certain requirements, which result from both process restrictions (layer thickness, component dimensions, etc.) and the functional properties of the manufactured component (mechanical strength, thermal conductivity, etc.). Both types of restrictions must be considered synergistically at the material, path, and component level. The functional performance of a component depends primarily on the properties of the cured material and the structural geometry for mechanical properties as well as other properties such as thermal insulation, sound insulation, etc. (Fig. 1).

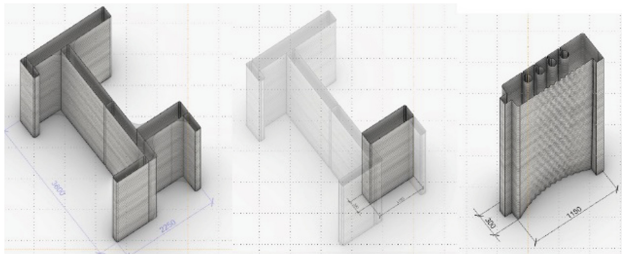


Fig. 1. Multifunctional AM element as developed from a assemblage of walls.

3 Joint Project “BauProAddi”

Goal of the government-sponsored research program “BauProAddi” (www.bauproaddi.eu) between the TU Berlin, the construction firm Ed. Züblin as well as other research institutes and industrial partners (Fig. 2) is the development of high-quality, fast and low-price AM processes in construction. Its uniqueness lies in an examination of the entire value chain from the formulation of the construction materials (from the binder and building chemicals up to the mix design of the AM-mortar and concrete), the design and manufacturing techniques with the print head as well as the adapted printing technology to the manufacturing of demonstrators and quality monitoring. The variety of expertise within the research consortium necessitated an integrated approach to handling the intense communication between the partners over the whole process chain as well as the handling of several types of data, ranging from complex building design models to instructions for robot control.

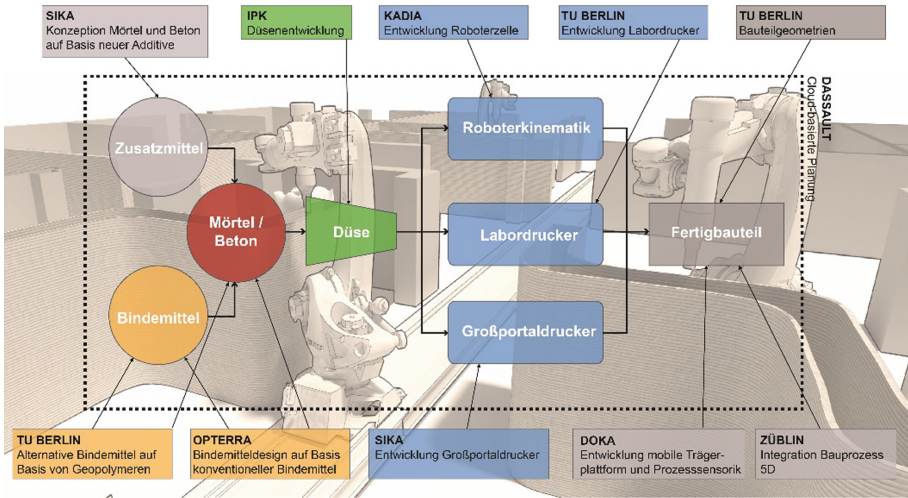


Fig. 2. BauProAddi Partners: TUB = TU Berlin, IPK = Fraunhofer IPK, KA = Kadia GmbH & Co, OP = OPTERRA GmbH, SD = Sika Germany GmbH, DO = Doka GmbH, ZÜB = Ed. Züblin AG

3.1 BIM to AM – Digital Fabrication Workflow

Building Information Modelling (BIM) is becoming more and more obligatory for construction projects worldwide. Therefore, further processing of BIM models through automated routines is critical for the integration of AM in construction. The subsequent chapter presents a workflow for slicing large wall-objects with respect to a distributed fabrication approach using the software platform of the associated partner Dassault Systèmes. This networking platform 3dExperience enables the collaboration of architects, engineers, scientists, and companies. All phases of the AM, beginning with design of parametric building components to the generation of tool paths as well as project coordination are summarized in a detailed BIM (Building Information Model) as a digital counterpart to the physical manufacturing devices and printed building elements.

3.2 Distributed Fabrication Approach

The distributed fabrication approach is a concept for a short-term integration of AM to learn through validation models described by machine-readable ontologies. The following thought experiment is conducted under the following “leap of faith” assumption: Big data and artificial intelligence will popularize a new layer of (data) complexity, making it easier to coordinate swarms of single-task robots rather than complicated machinery. Single-task robots are cheaper in production and exchangeable when malfunctioning without having to stop the construction process. As an intermediate step between future visions of automated construction sites and today’s reality, companies could develop validation models fed by conventional, off-the-shelf robots.

Multiple, collaborating robots present a scalable solution that is not limited by size, which is the case for large gantry printers. In comparison to a robotic arm, the gantry printer's printing area is defined by the boundaries of the system. On the contrary, the boundaries of a robotic arm are defined by its subset of components such as rails. Therefore, the total printing area of an open system is larger than the printing area of the smallest unit (in this case, the standalone robot). Since 6-axis robots are off-the-shelf products, the assumption for a short-term integration can be made. In addition to that, before further developing to real single-task robots, commercial robotic arms could perform various other tasks like drilling. Another advantage of using robotic arms is the availability of computer-aided manufacturing (CAM) software, helping to address the issue of integrating the new technology into existing modelling workflows, as described in the next section (Fig. 3).

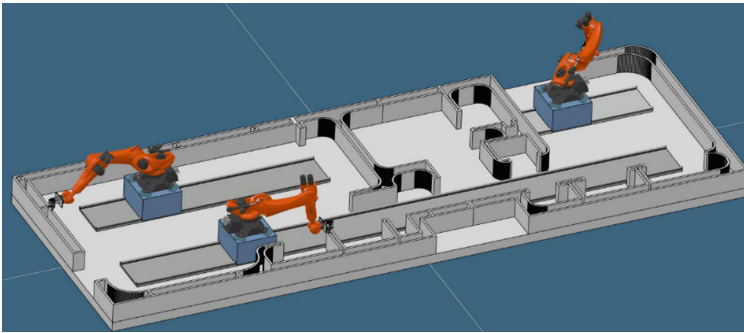


Fig. 3. Distributed robotic AM

3.3 Digital Workflow

In the research project the digital workflow for processing data from planning to production is implemented within the cloud-based 3DEXperience platform from Dassault Systèmes [13]. Having its roots in aviation and mechanical engineering, the software company has extended its portfolio from 3D product design to simulation, manufacturing, and nowadays AEC modules that run within one data environment. As an associated partner of the research project, Dassault Systèmes provided a tenant to the consortium, allowing the use of web applications for visual programming and a native installation for modelling, simulation and manufacturing tools connected through a gateway to the cloud. The developed workflow can be represented with the following steps (Fig. 4):

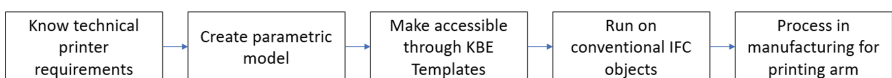


Fig. 4. Basic workflow steps.

The main element of the workflow is the Knowledge-based Engineering (KBE) template that is composed of one or more required inputs, an action and/or a set of rules. In the presented workflow, the required input is an Industry Foundation Class (IFC) wall object and the transformation action a generative algorithm. A set of rules could go as far as inheriting the business rules of a company about common practices or simple true-false queries on whether the wall is reinforced or not. Not only does the KBE template build the bridge from planning to production, but it also connects human knowledge coming from observations to binary code on a more abstract level. Following up on the action element, the generative algorithm was created in the web application xGen. In comparison to Rhino and Grasshopper, xGen works bidirectionally between the graphical and 3D representation. For example, when drawing a point on a line in the sketcher, two nodes with an edge are created in the graph.

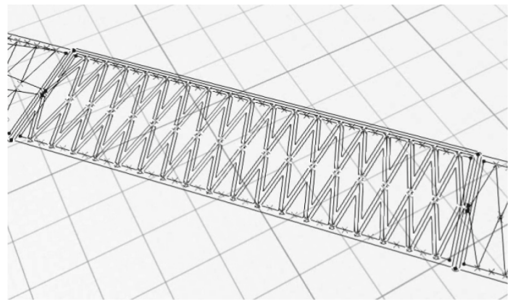


Fig. 5. Parametric model of the base layer of an unreinforced wall segment incl. track gauge

Figure 5 shows the base layer of one vertical wall segment. The total number of vertical elements is driven by a parameter defining the number of equally spaced elements and could further represent one printing cycle with respect to material and static requirements. Every printing cycle is defined by the total arc length s that allows the continuous buildup of the printed object based on experimental results. This is because the developed admixture consists of a 1.5 component mass that is pre-mixed by a continuous mixer before processed by the nozzle, while the opposing printing technology suggests portioning of the chemical admixtures at the nozzle in order to print a given object. Both technologies are compared in Table 1.

Table 1. Comparison of printing technologies with respect to material and arc

Printing technology	Constant	Variable
Arc dependence	Material composition	Arc
Material dependence	Arc	Material composition

It is subject of investigation which technology is better suited for a distributed fabrication approach since additional factors, such as material feeding, number of parallel printing robots, etc., are yet to be examined. As of today, the BauProAddi consortium experiments with both technologies, although focusing on solving the issue of resulting colt joints when keeping the material composition constant (Fig. 6).

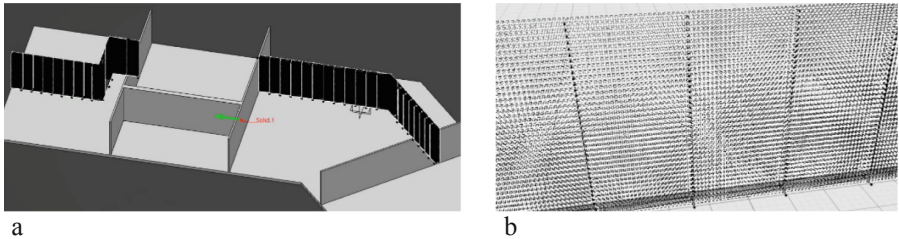


Fig. 6. Vertical slicing for a distributed fabrication approach. Sliced IFC building (a) and close-up of multiple segments (b)

The last step of the workflow consists of the generation of the toolpath from the sliced wall object. Due to the object-oriented character of the 3DExperience platform, a Production Plant Resource (PPR) object had to be created from the existing experimental setup of the robotic printing arm cell. In order to generate the toolpath from the sliced wall segment, various configurations had to be made in the manufacturing environment, including equipment allocation, controller definition, specification of twists and turns of the robot and other. In the final step, the toolpath was generated by following the curve which then allowed to export a true source file (.SRC) translated by a predefined KUKA parser.

3.4 Experimental Fabrication Approach

In the project, several wall elements with different functionalities were designed to be validated by experimental prints. Two extrusion-based printers were constructed to test the interplay between material design, manufacturing constraints and architectural properties [14]. First experimental prototypes were printed with a small ($400 \cdot 400 \cdot 400 \text{ mm}^3$) and a large ($2000 \cdot 2000 \cdot 2000 \text{ mm}^3$) self-constructed paste extruder printer, specially designed for printing with the need to control, change and stop the material flow instantly (Fig. 7a). Several concepts of adding additional functional layers into AM building elements were explored (Fig. 7b).

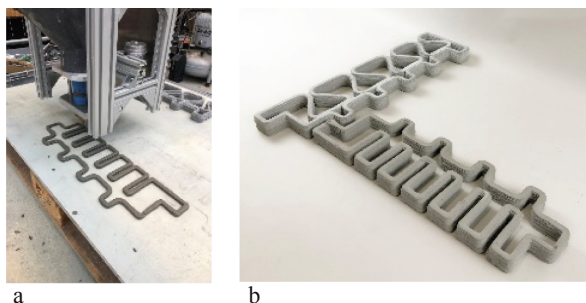


Fig. 7. Printed prototypes. a) Large paste extruder. b) Section of wall element.

A second mobile and shared setup between the partners included an exchangeable industrial robot (Kuka KR 90 six-axis robot) to test the interplay between the robot kinematics, a custom printhead and the material. Several printhead concepts were tested with an active deposition of additives within the printhead (Fig. 8).

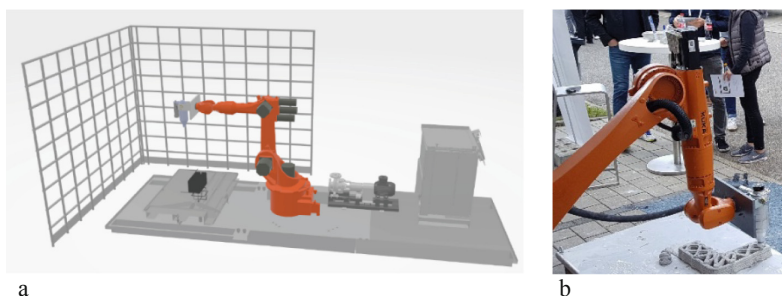


Fig. 8. Experimental setup for robotic AM, developed by project partner KADIA

4 Conclusions, Future Directions and Challenges

3D printing of full-scale construction components is still an emerging technology and as an alternative construction method is attracting increasing attention. While there are still major challenges in developing the appropriate material that can be extruded continuously and stacked up over one another without causing any deformation is equally important to consider a digital workflow which combines design with analysis to simulate both structural loads and material reactive properties to understand its behavior. This study examines only a small part of the software technology needed to accomplish its objectives. Our aim is to understand the complex interplay of material, process, and geometry in the production of concrete building elements, leading to the optimization of all three variables. With the integration and further development of BIM and its development towards process-based integration, it can also help mitigate some of the key challenges of a construction project such as construction planning and monitoring, effective communication, safety and procurement management. While 3D

printing can offer many advantages such as creating complex design, time saving and material saving, the need to abolish conventional methods completely may not be necessary. The future of construction is most likely to be an integrated process that allows organizations to take advantage of both conventional and 3D printing technologies at the same time.

Acknowledgement. The authors are thankful to the Federal Ministry of Education and Research for funding of the project BauProAddi (FKZ: 03XP0122A). Further acknowledgement goes to OPTERRA Zement GmbH and Sika Deutschland GmbH for the supply with the basic components for the printing materials.

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ACDC: The Admixture Controlled Digital Casting and Its Application to Thin Folded Concrete Structures

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Abstract. Digital concrete technologies aim to minimize or eliminate the need for formwork, produce less waste, and build material efficient designs at increased productivity. This paper discusses how Admixture Controlled Digital Casting (ACDC) could address these aims by producing thin folded structures. For the process, a set on demand concrete composition was used to achieve minimal deformations when robotically filling weakly supported formworks. The formworks were constructed from bendable materials such as foil, geotextile or paper tensed between a frame on top and bottom and could be reconfigured for different geometries. The prototypes were assembled and post-tensioned to achieve a one-to-one scale fully functional architectural roof element. With the demonstrator presented, ACDC challenges the way we think about casting and formworks in the construction industry at the age of the 4th industrial revolution.

Keywords: Digital casting · Set on demand · Deformations · Folded structures

1 Introduction

Digital fabrication technologies with concrete are subject to research due to their potential to improve the efficiency and sustainability of the construction industry [1]. These novel fabrication methods aim to decrease the labour and formwork needed for concrete construction [2]. Thus, they also allow for revisiting the historical concept of folded structures providing reduced material use is combined with increased structural capacity due to its shape [3]. This paper focuses on a specific digital concrete process, Admixture Controlled Digital Casting (ACDC), as it merges characteristics of different digital concrete processes according to the need of producing thin folded concrete elements. ACDC is part of the broader family of digital casting processes [4].

ACDC uses a robotic arm to cast a set on demand material into weakly supported formworks (see Fig. 2 and Sect. 2.1 for description of the fabrication setup). The concept for set on demand material was first applied for digital fabrication in the Smart

Dynamic Casting process [5–7]. While the material is deposited by a robotic arm, similar to Layered Extrusion [8]. Although ACDC requires a formwork, with the gradual deposition and initially fluid and then fast hardening material it provides the possibility to build it from thin, flexible or bendable materials that would burst or largely deform with traditional casting techniques (Fig. 1).

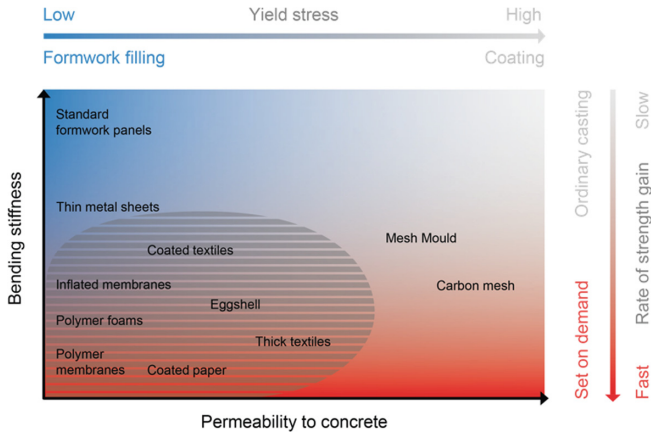


Fig. 1. Possibilities of different formwork materials based on the strength evolution and rheology of the concrete filled into them. ACDC has potential in the striped zone.

Two potential set on demand mortars potentially suitable for the needs of ACDC were previously developed in lab tests and published in [9], however, those formulations had to be tested with the continuous material processing of the robotic setup discussed in Sect. 3.1. These initial experiments follow an experimental approach to quantify material properties, especially yield stress, and relate them to formwork deformations on a straight geometry to define the most suitable mix and fabrication parameters for the production of the large folded structure in the second experimental phase. Compared to the initial tests, the second experimental phase takes a more empirical approach to explore the influence of different formwork materials, folded geometries with changing cross-section, reinforcement integration to showcase the fabrication potential and materiality of ACDC.

2 Materials and Methods

In this paper, two different retarded base mix formulations were tested for ACDC: an UHPC (noted ‘mix U’) with a mix design based on [10] and a self-compacting mortar (noted ‘mix S’) adjusted from previous SDC formulations [9, 11]. ‘U’ comprises 0.1–0.4 mm silica sand, a CEM I 52.5 N Portland cement, silica fume, two types of limestone fillers while ‘S’ contains 0–4 mm siliceous sand aggregates, a CEM I 52.5R Portland cement and silica fume. For both base mixes, the admixtures (sucrose 99.5%

from Sigma-Aldrich as retarder and BASF MasterGlenium ACE 30 as superplasticizer) are pre-dissolved in the water and added together to the powder parts. Then ‘U’ is mixed for 10 min and ‘S’ for 7 min with a forced action mixer in batches of 30 L.

The wet base mixes are poured into a progressive cavity pump that continuously delivers them to the mixing reactor for acceleration. ‘Mix U’ is activated with an aluminium sulfate solution with 14% concentration by mass. ‘Mix S’ is accelerated with a combination of an activator (aluminium sulfate solution with 22.0% concentration by mass) and a flow enhancer (superplasticizer). The amounts are based on [9] and are represented in Table 1. The dosing happens at the robotic setup (Fig. 2) by one (U_A) or two peristaltic pumps (S_A_SP). The concrete dispensed by overflow from the reactor after mixing is called the accelerated concrete, the name of the accelerated mix, such as ‘S_A_4_SP4.28’, indicates the activator dosage (4%) and the superplasticizer amount 4.48 g/l concrete. In the second experimental phase, the superplasticizer dosage at casting slightly differs from the ones indicated in Table 1, however, the amount of addition can be seen in the mix name.

Table 1. Base mix formulations and accelerator amounts for the two mortars used here

Retarded Mix [kg/m ³]	U		S	
Sand	616.4		1367.6	
Cement	547.5		615.1	
Silica fume	191.6		32.4	
Betocarb-SL	183.1			
Betoflow-D	419.1			
Water	192.2		247.2	
Superplasticizer	6.00		1.55	
Sucrose	1.33		0.68	
Ca(NO ₃) ₂	0.03			
Accelerator [g/l _{concrete}]	U_A		S_A SP	
Al ₂ (SO ₄) ₃ · 18H ₂ O*	13.7 (2.5%)	21.9 (4.0%)	24.6 (4.0%)	24.6 (4.0%)
Water	36.5	58.4	32.8	32.8
Superplasticizer**			3.45	4.28

*percentage with respect to cement mass **mass of solution

2.1 Robotic Experiments with Admixture Controlled Digital Casting

Figure 2 presents the setup for ACDC consisting of a 6-axis robotic arm (A), that is connected to a progressive cavity pump (B) at its end-effector, the mixing reactor (C), where the retarded concrete is intermixed with the accelerator dosed by one or two peristaltic pumps. Then the overflowing accelerated concrete is cast into stationary weakly supported formworks with a back and forth motion between the two ends along the straight or folded geometry (D1 and D2). The fabrication parameters such as robot speed, filling path and accelerator dosage are defined and the sensory feedback is recorded by the computer (E).

Initial Experiments. The most suitable material composition for the continuous processing of ACDC is defined by filling straight horizontally tensed formworks with 0.5 mm PVC walls and $95 \times 5 \times 40$ cm inner dimensions. Both base mixes and varying accelerator dosages were tested to achieve less than 15 mm horizontal maximum displacement on the formwork walls. The flow rate of the mortar pump was an aggregate-size dependent constant, however, the robot speed was kept as a variable.

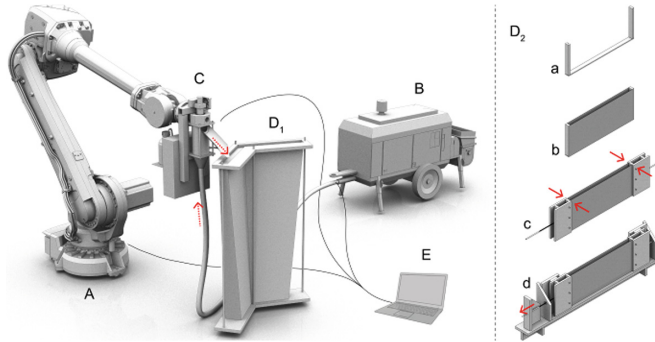


Fig. 2. Robotic setup for Admixture Controlled Digital Casting (ACDC) discussed above and steps for assembling the straight formwork: a) frame, b) mounting the walls c) clamping into the holder, d) tensioning with a spring.

Material Tests. Accelerated concrete samples were collected right before filling the formworks. Their qualitative hydration kinetics were studied with isothermal calorimetry (I-Cal8000) and their strength evolution was determined with slow penetration tests [7] using a conical penetration tip (30 mm height and 10 mm radius) at a penetration rate of 20 mm/h with a Zwick testing machine at times presented in Table 2.

Table 2. Experiment timings and additional parameters for the initial tests

Mix	v_{robot} [mm/s]	Sample [hh: mm]	Slow pen. [hh: mm]	Cal. [hh: mm]	Grid	Force sensor	Vertical building rate [m/h]
U_A_2.5	100	01:20	01:24	01:28	x		0.71
U_A_4	50	01:11	01:15	01:19	x		0.71
U_A_4_rep	20	01:25	01:33	01:37	x		0.71
S_A_4_SP3.45	20	01:47	01:50	01:53	x		2.34
S_A_4_SP4.28	20	01:30	01:38	01:44			2.34
S_A_4_SP4.92	70					x	2.34
S_A_4_SP4.25	20					x	2.34
S_A_4_SP4.42	20					x	2.34

Deformation Tests. The deformations of the formwork walls originating in the casting process were investigated after fabrication with a dial indicator through a grid with 4×8 measurement points (Fig. 3: A). Then, continuous measurements were also performed by recording the forces with a Zemic S-type 100 kg load cell at a single point in the middle of the formwork when the most suitable S_A_SP composition was cast at 70 mm/s and 20 mm/s robot speeds but constant concrete flow rate (Fig. 3: B1 and B2). As a reference, this second type of measurement was repeated with a traditional wooden formwork through a hole for the sensor. On the sensor side, a 0.3 mm thick PVC foil provided separation between the fresh concrete and sensor similarly to [6].

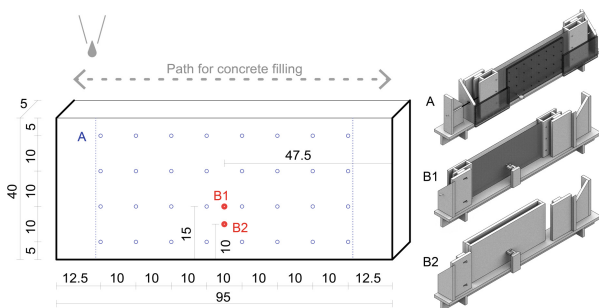


Fig. 3. Deformation measurements for straight formworks with A) the front grid defining point where the displacement is measured with a hand-held dial indicator or with B) a load cell

Folded Structure Demonstrator. With the most suitable material composition (S_A_4_SP4.28) and robot speed (20 mm/s), the casting experiments continued with 1 m tall folded formworks prepared from different light formwork materials (0.2 mm PE foil, geotextile, 1.15 mm RAM-board) tensioned between a lower and upper frame (Fig. 4). They showed variations in fold angle and cross-section along their height thus variations in robot path and layer height were also explored. Then, they were designed as parts of a larger roof segment thus including tubes for post-tensioning cables and positioning pins acting as shear keys at the connections of the elements.

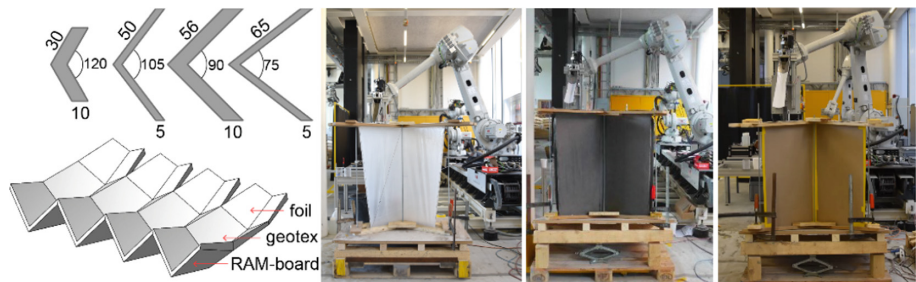


Fig. 4. The design of the folded roof section with varying cross-section [cm] consisting of three elements cast in weakly supported formwork with the robotic setup.

3 Results

3.1 Initial Experiments

Material Tests. The calorimetry results are represented in Fig. 5(left). Qualitatively, a high reaction rate can be observed after activation for both U_A_4 and S_A_4 mixes (the retarded base mixes with the same composition are reported in [9]). The single hydration peaks of the U_A samples appear at similar times even with slightly less accelerator while the silicate and aluminate reaction peaks of the S_A_SP mixes are occurring later with smaller maximum when more superplasticizer is added upon acceleration.

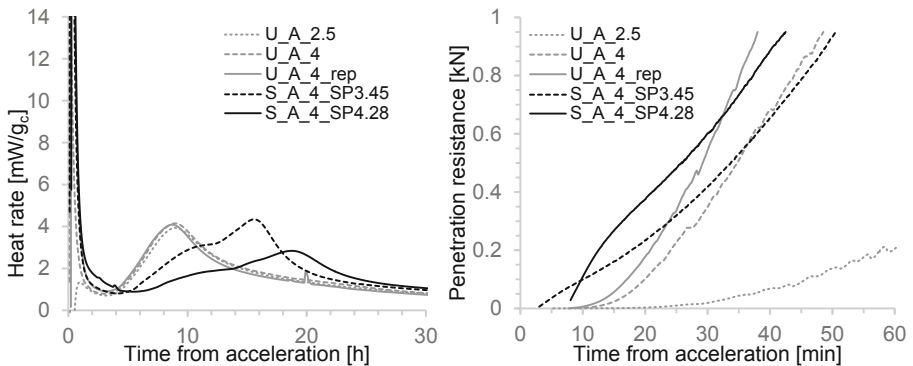


Fig. 5. Evolution of U_A and S_A_SP mixes with different accelerator dosages, left) Heat rate, b) penetrometer resistance.

The penetration resistance recorded with slow penetration tests in Fig. 5(right) increases with material age and more so with higher aluminium sulfate dosages for all accelerated U_A and S_A_SP samples similarly as previously reported in [7, 9]. The S_A_SP mix variants show an immediate rapid increase of penetration resistance with a lower starting point for higher superplasticizer addition while the strength build-up of the U_A compositions is initially delayed. However, later, the strength evolution of the U_A_4 mixes is faster than of the S_A_4 mixes.

Deformation Tests. The results of the deformation grid measurements are plotted by overlaying the coloured displacement graphs interpolated from the measurements recorded on the front of the prototypes. Thus, the filling characteristics can be observed together with the degree of deformation in Fig. 6.

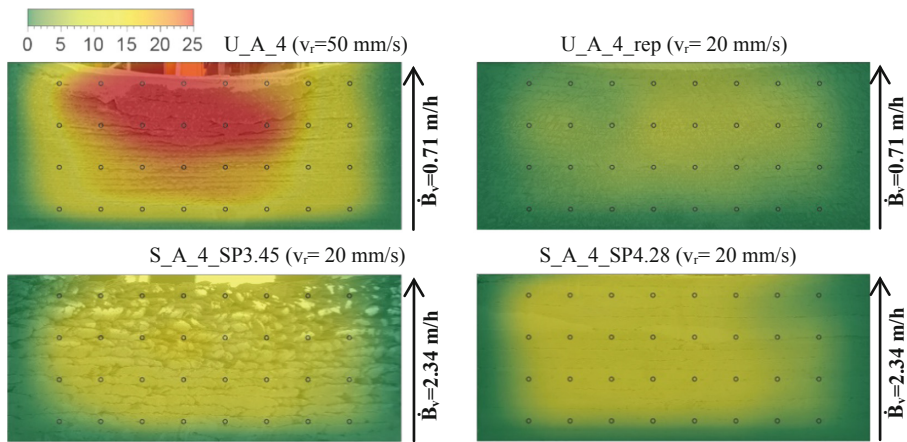


Fig. 6. Grid measurements (in mm) after casting at the specified building rates

With U_A_2.5, the deformations were too large for the setup to detect. Regardless of the open time of U_A_4 after acceleration, with the low vertical building rate and slow robot speed, the deformations were minimal. Further, the deformations were at a similar range even at high vertical building rate with S_A_4_SP, where the slightly increased superplasticizer addition improved the formwork filling significantly.

The results of continuous force measurements on the weak straight formworks are plotted in Fig. 7, indicating the times of each robot pass with dashed lines for both robot speeds. The filling increases the load on the formwork walls even before the concrete reaches the sensor height (red dashed line). The load is higher with higher robot speed. Then the steps with which the load increases are largest around the sensor height and reach a plateau after approximately 2.5 min for both samples (corresponding to 3 and 10 layers respectively with the slow and fast speeds).

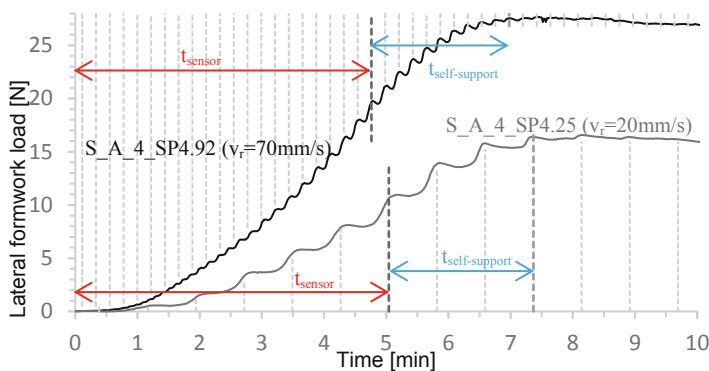


Fig. 7. Forces recorded on the formwork wall during casting with different robot speeds

Compared to the weak formwork tests, with the rigid wood formwork, no significant force can be recorded before reaching the sensor height, however, the plateau appears here as well after a similar amount of time and the same amount of new layers.

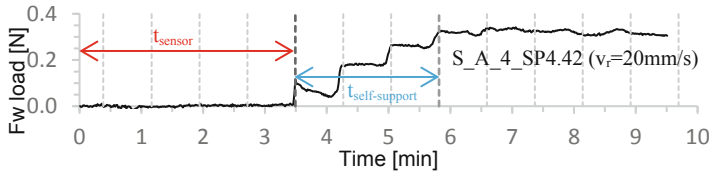


Fig. 8. Forces recorded through a hole during casting into a traditional wooden formwork

3.2 Folded Structure Demonstrator

All three pieces of the demonstrator were produced successfully in the first trial and demoulded a week after. The foil formwork was easy to remove and provided a shiny smooth surface. However, the adhesion of geotextile and RAM-board on the prototype required additional effort at demoulding. Geotextile remains were brushed off without a problem and left the surface ‘furry’ while the RAM-board was washed off with high-pressure water slightly colouring the surface and increasing the visibility of the layers. The assembly was guided by the positioning pins that showed sufficient accuracy and no cracks developed during post-tensioning (Fig. 9).



Fig. 9. Prototype (foil formwork) and post-tensioned folded roof section

4 Discussion

Qualitatively the material tests are in good agreement with the deformation tests. The high heat release in the first hour (seen from calorimetry in Fig. 5) corresponds to extensive formation of hydration products responsible for rapid strength evolution (Fig. 6) leading to the minimal deformations (Fig. 6) during ACDC.

Figure 10 provides a graphical representation of the maximum amount of fresh layers influencing the deformations at the bottom based on the von Mises criterion. We

expect that when the yield stress of the concrete is higher than half the hydrostatic pressure of the concrete above no more deformations occur. The yield stress is approximated from the slow penetration force with a coefficient of 180 Pa/N according to [9] for both U and S mortars with high accelerator dosage. The pressure due to filling increases with time as additional layers are deposited (due to the linear robot movement its steps vary at different formwork positions). Indeed, Fig. 10 shows that self-support is expected for S_A_4 at 3 min. Although it takes longer for the U_A compositions to exceed the vertical pressure and become self-supporting, the building rate is lower, thus explaining the low deformations seen in Fig. 6. The S_A_SP mixes reach self-support and stop deforming at a similar vertical pressure but in a lot shorter time.

The time needed to reach self-support with S_A_SP can also be read from the force measurements in Fig. 7 and Fig. 8. No additional force is recorded from the fresh concrete layers both in the rigid box and in the weak formwork after approximately 2.5 min showing good agreement with Fig. 10b. Additionally, the deformation grid could capture, but could not explain, the effect of higher robot speed disturbing the structural build-up of the previous layers resulting in larger deformations in Fig. 6.

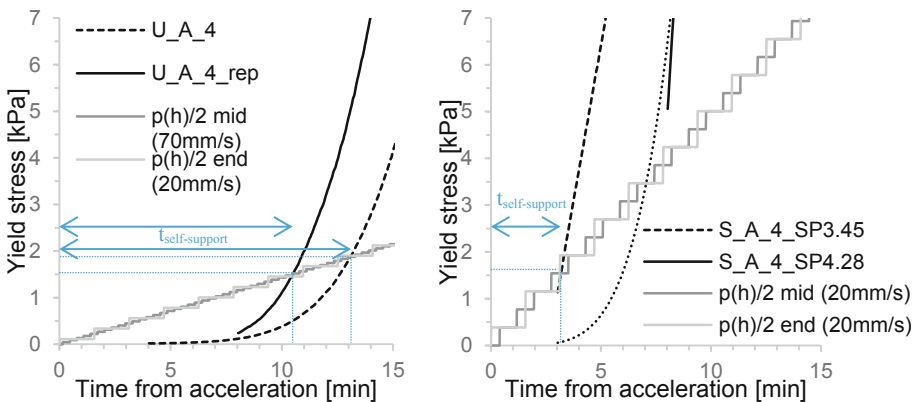


Fig. 10. Comparison of yield stress evolution and hydrostatic pressure increase over time. (Unfortunately, the measurement of S_A_4_SP4.28 was started too late to discuss it here.)

Based on the material and deformation tests, we determined a suitable concrete composition and robot speed for the fabrication of the folded structure demonstrator. Although both mix compositions could result in low deformations, the experiments continued with S_A_4_SP due to its higher vertical building rate and its robustness by the additional degree of freedom with the superplasticizer dosage. Slight changes in superplasticizer amount could compensate for day-to-day variations of the mix, different environmental conditions or changes in cross-section. Further, the lower plastic viscosity of S_A_SP mixes provides better formwork filling and ease of handling.

Despite the unknown exact resistance to the hydrostatic pressure of the different formwork materials, the tensioning logic between the lower and upper frame proved a successful strategy to produce one-to-one scale folded elements by ACDC. The assembly

of these prototypes is a proof of concept for a system where the tolerances are low at connection surfaces, however minimal deformations are allowed leaving space for the architectural expression of ACDC from different formwork materials.

5 Conclusion

Digital Casting and more specifically Admixture Controlled Digital Casting (ACDC) addresses the problem of high formwork pressure with self-compacting concrete. It shows that less formwork is required by robotically casting a set on demand composition adapted to in-line continuous processing. Importantly, yield stress measurements allowed to predict the time at which self-support deformations plateaus are achieved.

Further, ACDC was robust enough to cope with the increased uncertainty of the less controlled fabrication environment shown at the production of three thin folded prototypes without the need for repetition. In summary, ACDC and more generally Digital Casting shows that formworks of the future may be light, using a small amount of potentially recycled materials instead of bulky constructions.

Acknowledgements. The research is conducted in the National Competence Centre of Research (NCCR) Digital Fabrication funded by the SNSF at ETH Zürich. The authors thank Heinz Richner, Andi Reusser, Michael Lyrenmann, Philippe Fleischmann, Bruno Pinto Aranda for technical assistance and Alan Colmant, Marius Graf, Nicolas Neff for their experimental work providing the base of this paper with their Bachelor thesis.

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Robot-Controlled Fabrication of Sprayed Concrete Elements as a Cyber-Physical-System

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Abstract. In order to make the mass production of free-formed concrete elements for architectural and engineering projects possible and financially achievable new ways of production has to be developed. This paper presents a robot-controlled fabrication of sprayed concrete elements as a cyber-physical-system. It utilizes the concept of Industry 4.0 and IoT-technology together with automatized fabrication methods and developed sophisticated software solutions for communication, planning, modeling and analyzing. This concept bases on a decentralized system of fabrication, analytic and path-planning services connected with a mqtt-communication protocol. Next to the system- and software development a special material based on concrete is developed, *shotcrete*, which is adapted to needs for the application of spraying.

Keywords: Concrete façade elements · Robotic fabrication · UHPC · Shotcrete · Cyber physical system · Industry 4.0

1 Introduction

Concrete façade elements find high sales worldwide in the field of façade technology. The demand is constantly increasing, as are the requirements for architects, structural engineers and construction industry. In addition to the demand for higher qualities and mechanically more efficient materials, there is also an increasing interest in geometrically more complex shaped facade elements.

The traditional concrete or precast industry has so far hardly been able to meet these special requirements, as it is mainly oriented towards the usual market standards and certifications and also sticks to the established simple production methods. A common established production method for façade elements is the casting of concrete façade panels into large molds (formworks), with inserts of steel or fiber fabrics and subsequent horizontal storage of the elements for several weeks to allow the material to harden. Typical subsequent finishing methods include cutting the panel to size and drilling holes for anchors. Alternatively, 10 mm–12 mm thick concrete slabs are ‘extruded’ in a continuous process. The final processing of these endless plates is done analogously. Some manufacturers can slightly bend the panels produced in this way while still fresh to produce a deformed façade element. The implementation of multi-curved façade elements, which differ from each other, but which can still be produced in larger series without causing a cost-intensive, considerable manual effort, is

technically hardly possible nowadays (cf. term “mass customized”). The technical production processes of the existing production companies do not allow for these possibilities - facades with smaller surface areas and complex geometric shapes are usually produced manually in medium-sized factories.

The demand for such complex facades is increasing on the part of architects - this demand cannot be met at present. If the prerequisites for a) production and b) tools for architects to plan such complex facades existed, they would be realized. This gap is to be closed with the new production process involving a new type of concrete-based, fast-hardening material and in particular a “cyber physical systems” approach in this project: In order to realize the concept of “mass customization”, industrial production is to be dovetailed with modern information and communication technology. The technical basis for this are intelligent and digitally networked systems. With their help, a largely self-organized production should become possible: People, machines, plants, logistics and products communicate and cooperate directly with each other in the technology known as “Industry 4.0”. Networking should make it possible to optimize not just one production step, but also an entire value chain. The network should also cover all phases of the product’s life cycle - from the idea of a product to its development, manufacture, use, maintenance and recycling. At present, there are no advanced, fully digital systems for the automated concreting of complex components.

This paper will describe a concept and solution of a Cyber-Physical-System for a robot-controlled fabrication of sprayed concrete elements. It is focusing on the whole process, robotic, software, hardware and material dependencies.

2 Summary of the General Objectives

To fulfill this growing need of lightweight, concrete free forms new production line has to be developed where geometrically complex facade elements are produced in an automated, robot-controlled manufacturing process from a fast-curing special concrete, shotcrete. The planning of the facade elements as well as the control of the production is carried out using a “Cyber Physical System” approach with the following general targets:

- Development of a novel, fast curing shotcrete based on HPC (High Performance Concrete) suitable for the automated, robot-controlled production of concrete facade elements
- Development of shotcrete tools and robotics, by means of which the novel shotcrete can be processed fully automatically into geometrically complex facade elements.
- Development of a “Cyber Physical System” for planning, control and production of elements (Industry 4.0)
- Development of a pilot plant in which all sub-components are linked together, and which demonstrates the functionality of the overall concept.

3 Cyber-Physical Production System for Concrete Facades

In terms of Industry 4.0, this project aims to develop an innovative process for the production of 3D concrete façade elements, in which autonomous robot systems communicate with each other and dynamically adapt the production steps and requirements via data exchange. Software tools are used to generate parametric facade elements, which store their data in cloud data storage and transfer them to the CPS production plant. The robot system is built up modularly, without direct cabling of the complete line. The individual components interact with each other via the cloud system and an IoT-protocol and adjust their production autonomously [1]. If there is a change in the production chain, the system recognizes this and acts accordingly.

The complete production chain is digitalized from the first design step of the architect, converted into data formats and transferred to the systems (Fig. 1). But even after the end of production, the facade elements are still ‘digitalized’ having digital twins and can be clearly allocated and thus installed and re-produced at any time. The system automatically generates a code for modern BIM systems and enables complete digitalization from A to Z.

The robotic system utilizes UR10 robots from Universal Robots, RPLidar and Primesense scanners, concrete pump from PFT and individually developed nozzles, adapters. The software used in the project are mostly custom made solutions but also utilize products from RoboDK and Rhino3D with Grasshopper.

3.1 Non-linear Production Process vs. Linear Production Process

In this context, “linear approach” is a type of machine control that has very few influencing parameters. This approach is very effective in the production of repeating parts. In an individualized mass production, under constantly changing influencing variables, with cross-references between the part and whole [2], the system must recognize these parameters and react to them - this approach is called “non-linear” and is applied in this project.

3.2 Design to Production to Design

A new type of software packages is designed for the interpretation of 3D models for processing with multi-axis robots, which is therefore strongly related to industry and construction. It is developed on the assumption that each component to be machined is different and the robots generate paths “on the go”, unlike the usual practice up to now. This means that spraying paths are not generated out of a CAD-model as usual, rather than out of a scanned mold following an autonomous algorithm. The sprayed result is been scanned and compared with the CAD-model and process of spraying and scanning is repeated until it fulfills the thickness requirements. There is currently no technical solution on the market for the application of automated production of individual components by creating negative forms and applying concrete layers.

One of the technical solutions is the application of a self-learning system such as Reinforcement Learning (RL), which addresses a feedback in several production stages with the goal of self-improvement of the automated tasks. RL is a machine learning

technique where the observed model, here the different stages of the mold and final sprayed part, and the actions of the robot are evaluated and a reward factor is determined and increased in an iterative process. The final goal is to have a feedback from production to the design that needs the development of our own system of categorization with the help of structured predictions, which will help us to design models that are not unbuildable in relation to production peculiarities or that do not deviate significantly from the intended model. RL is usually used as a recommendation or process optimization system [3].

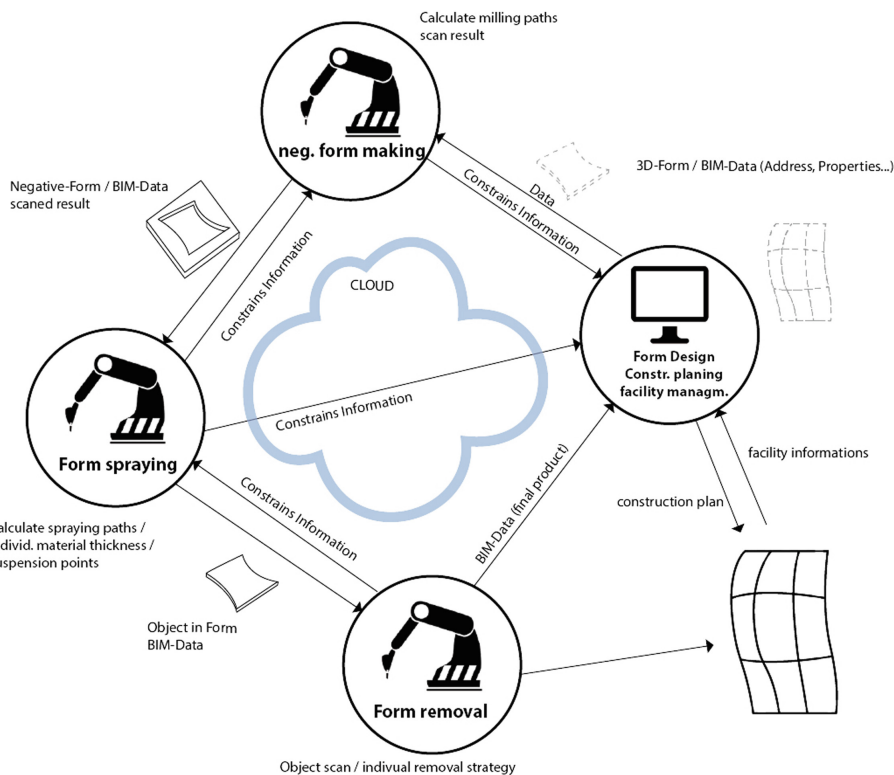


Fig. 1. Scheme of production process with a CPS system.

3.3 Production to Assembly

This package aims at software-specific solutions with regard to the special features of architectural and constructive production: handling/final formwork of larger and shape-specific components and their installation. This process is very labor-intensive due to the highly individual nature, size and weight of individual components. In addition, there is the enormous effort to prepare the components for installation (measuring for final assembly).

Due to the planned continuous digital chain, it is possible to follow a digital description of the component in every phase of production, even if the production steps are physically separated. So far, as there is no continuous digital chain (comparable to e.g. car manufacturing) in a typical project-oriented construction industry [4], these kinds of concepts are novel for production of concrete elements. Our approach follows a mixture between central and decentralized data processing (Fig. 2).

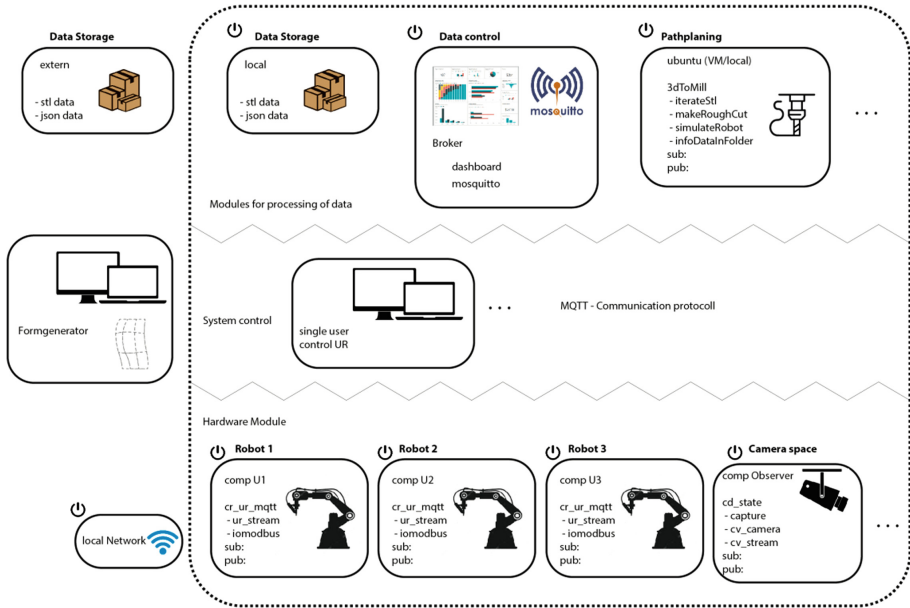


Fig. 2. System components of the software packages. The illustration is representing external and internal components. On the right side the components are connected with the MQTT-protocol. Inside the frames the main functions are listed and for some component the subscribing (sub) and/or publishing (pub) data

3.4 Physical Situation Recognition

The physical situation recognition differs for each system component (system machine) and is decisive for the success of the in-between measuring steps. Situations before and after processing are detected (Fig. 3), compared with the virtual model and processed. The main focus is on the independent “seeing” of the units (e.g. when feeding in raw blocks before and after the milling process or defining gripping points during the removal). For this purpose, mainly 3D and 2D data are acquired and processed and fixed scanning units per system component are necessary.

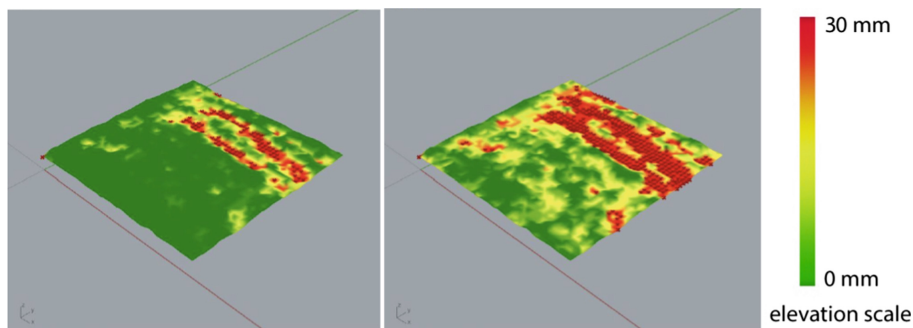


Fig. 3. Thickness evaluation of sprayed layer. A fixed 3D-scanner above the spraying table is first scanning the unsprayed mold (left) and, after spraying, scanning the next layer (right).

3.5 Planning and Foresighted, Fully or Partially Autonomous Action

By adjusting the constraint parameters (i.e. what margin a machine has for each specific task) in the system, the components act in a forward-looking manner (tasks are adapted from machine to machine in a component-related manner). If the system components are replaced/changed or if external processing is carried out, a calibration must be carried out to sound out the scope for action. The aim is to maximize the degree of autonomy of the individual system components.

3.6 Ultra High Performance Concrete - *Shotcrete*

The “free geometry” of façade elements sought in the market requires developments in materiality and production. The UHPC (Ultra High Performance Concrete), planned as the performance material for this development, is subject to certain physical boundary conditions, which are owed to the building material “concrete”. A concrete-based material must first have enough low-viscosity properties for spraying, but still be sufficiently strong for use in the negative formwork and should harden in a precisely controlled short time after the spray-process to prevent deformation under the influence of gravity. Adding suitable fibers reinforces the mechanical stability of the material, which results in a sufficiently high compressive and flexural strength during the hardening process, so that the produced part does not deform again during movement processes in the further course of processing. The composition of the *shotcrete* must therefore be sufficient for processing by the *shotcrete* robot (viscosity, adhesion, setting time, etc.). In addition, the hardened material must meet the final requirements of the exposed facade surface: for this purpose, the surface properties (smooth, scratch-resistant, UV-resistant, weather-resistant, coloring etc.) but also the mechanical stability must be taken into account.

The material development for the *shotcrete* robot requires a different technological approach than the usual concrete development: Concrete designed for mass production in the conventional production process is mixed in compulsory mixers, whereby the aggregate contributes to the homogenization of the concrete. Water and the proportion of superplasticizer regulate the mechanical strength of the concrete and the processing

properties in addition to the properties of the cement used and the physic-chemical properties of the other raw materials. In simple terms, conventional concrete is placed into a formwork by means of gravity via concrete pumps or other transport systems and then mechanically compacted by vibration.

Other than the shotcrete-printing [5], this new type of fine shotcrete described here for use in facade production by means of robotics is carried out with a special developed mixing and transport system; the process implements different viscosities of the material at different points in the process as well as a faster strength development when sprayed into a mold. The solution for the material development is based on UHPC (Ultra High Performance Concrete) as a ready mix, developed by the company G.tecz Engineering GmbH. The following differences in material and production are to be considered.

Material shotcrete:

- Controlling viscosity as a function of time. Spreading measurement with a small cylinder of the self-levelling fast flow UHPC 35 cm in 1.2 s to 17 cm with the classic Hägermann test
- Controlling strength development as a function of time. From 10 Mpa compressive strength after several minutes to 130 Mpa after 7days
- Highly reactive cements but comparatively low proportions in the formulation
- Qualified raw materials: sand, stone flour, superplasticizer and other auxiliary and raw materials
- The production optionally allows the adjustment of concrete strengths according to its location in the concrete element.

Production:

- Mixing takes place in a special modified batch mixer, not in a compulsory mixer as usual
- The mixing volume and mixing time is considerably lower and shorter and must be taken into account in the formulation
- The concrete material must not contain any coarse aggregates (spray nozzle) and is therefore a pure concrete matrix with grain sizes <1 mm
- In this special continuous production process, the mixing energy, water supply, etc. must be permanently controlled
- The material is a highly packing density optimized powder that easily compacts in the material feed. The feed from the silo system is adapted to this.

Application:

- The material is sprayed onto a (negative) mold or surface (Fig. 4). The surface must be of high quality; spray mist (from concrete fine dust) is not desired. The adhesion properties are adjusted by applying chemical bonding agents.
- Depending on the inclination of the surface, the material must adhere to it and must not run off; at the same time, the material must be 'liquid' enough over a defined period of time to bond with the sprayed-on adjacent layer. This is adjusted by a chemical setting accelerators in the formulation .



Fig. 4. Spraying test on a complex mold

3.7 Shotcrete Nozzle

Our research has shown that shotcrete nozzles commonly available on the market are not suitable for use with the new UHPC shotcrete. Due to the viscosity of the material, the concrete behaves differently when it exits the nozzle compared to e.g. sprayed plaster. The fineness of the material leads, similar to paints, to a strong scattering and a spray mist that wets the adjacent formwork surface. Nozzles were therefore developed which convey the medium more compactly out of the nozzle. The 3D printed nozzles were practically tested in different sensing processes. The following illustration shows an extract of the developments (Fig. 5).

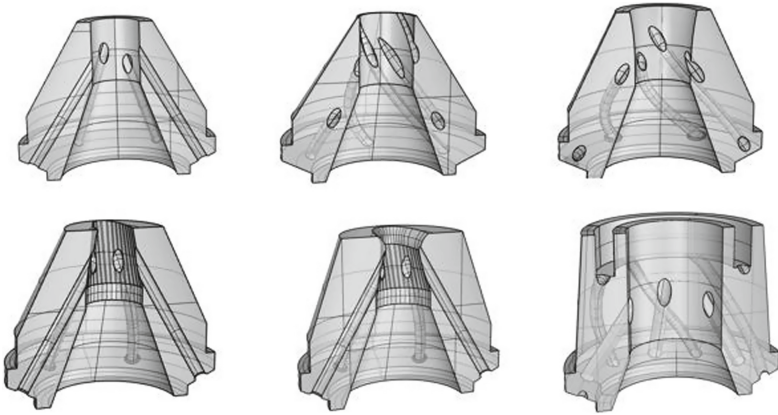


Fig. 5. 3D-printed prototypes of nozzles for testing

3.8 Software-Hardware Development Within the Project

The Cyber Physical System is been designed based on 6-axis robots and other fully automatic machines. Depending on the task in the production chain, the robots are having standard or specialized end-effectors for the creation of the negative molds or the spraying of the concrete or the post-processing (smoothing, drilling, cutting, etc.).

The algorithms that are developed cover several areas depending on the production stage:

- Data exchange system based on the robust and lightweight Message Queuing Telemetry Transport (MQTT)-protocol that supports decentralized service management based on subscribing and publishing of data packages. This incorporates the development of a framework where every unit, robots, scanner and computers in the system, act as a service with clear define role. This framework also manages the visual supervision of the process and keeping the control over the each steps trough a dashboard in a browser.
- Independent path creation using BIM data (milling, spraying, density, thickness, suspension points) retrieved from the shape generator (designer, architect, contractor). There is currently no robotics technology in the construction industry that performs these tasks using BIM data. For milling tasks optimization machine learning (ML)-algorithms are used for the expected large search space of the problem, especially for undercutting's. Several different spraying path strategies are developed that cover sharp edges or surface areas.
- Simulation of the robot movement is important to prevent singularities and testing the boundaries or the workspace. This process will repeat together with the path creation process until a movement version is found without any collisions and singularities (Fig. 6).

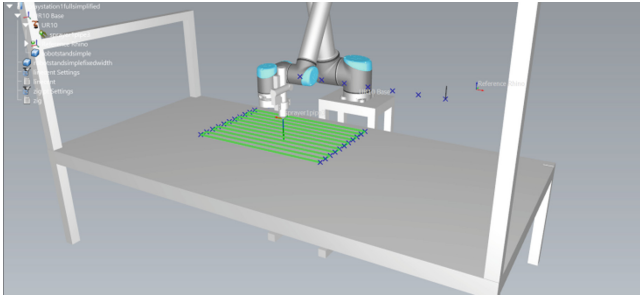


Fig. 6. One of the production tools as virtual model. Here a 6-axes-robot is simulating parallel path spraying.

- During the production process data is gathered by scanning and analyzed for constraint and tolerance parameters. One of the most important steps is to evaluate the actual thickness of the sprayed material during the production. An iterative scanning and path adaptation process does this and the robot will spray layers until the desired thickness is reached (Fig. 7).
- A continuous digital fingerprint (documentation of process data) in all phases of processing is made up to facility management of the installed component by cloud-based information acquisition and object allocation. Similar to other industries RFID chips or barcodes are used for identification and comparison with the data-base. The new algorithmic approach refers to the detection of deviations, the automatic comparison with other system actors and the establishment of a tolerance range (image processing, categorization).



Fig. 7. Concrete spraying (left) and robot position during the scanning process (right)- The robot and the pump-tubes are covered with a protective suit

4 Conclusion and Further Development

At this stage of development of the robot-controlled fabrication of sprayed concrete elements as a cyber-physical-system we can observe the benefits of a totally controlled production process with straight path planning, movement, digital analysis and correction in almost complete automatized manner. It comes out that the decisions for a decentralized process management is very good of quickly building up a testing production as hardware and software debugging is not influencing the running of other parts. The exchange of some services during testing is also possible. Yet for getting reliable data that can be used for tuning the system towards desired production system much more tests have to be made. The most improvements can be done in:

- Concrete pump system with better handling and eventually combined with a concrete mixture setup
- Human-machine interaction. The use of mobile tablets enables a real-time comparison (cyber-physical equivalence) of the virtual model/data with the actually built intermediate phases of the production. The display of critical areas with increased tolerance deviations is possible.
- Evolution: strategies of self-organization and adaptation in the production process. Adjustments of structures to changes in the market, production conditions and volume fluctuations must be checked on this system. Comparable strategies of self-organization in the building industry are not known and have to be developed with regard to automated production processes.

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Reinforced Particle-Bed Printing by Combination of the Selective Paste Intrusion Method with Wire and Arc Additive Manufacturing – A First Feasibility Study

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Abstract. The selective paste intrusion (SPI) is a particle-bed based Additive Manufacturing technology, which spreads particles in small layers and bonds them locally with cement paste. One advantage of this technology compared to other AM processes is that no support structures for cantilevers are required. Furthermore, SPI-made components achieve almost isotropic compressive strength (>70 MPa), high durability, and shape accuracy. However, to qualify the SPI process for the production of structural concrete elements, the inclusion of reinforcement is necessary.

This paper presents an approach to print the reinforcement during SPI simultaneously by using Wire and Arc Additive Manufacturing (WAAM). WAAM enables the fabrication of geometrically complex steel reinforcement structures with high build-up rates, whereby properties similar to those of construction steel can be achieved. This allows producing reinforced concrete structures according to the principle “form follows force”, which leads to ecological and economical components.

The major challenge that arises from the combination of WAAM and SPI is the occurrence of high temperatures (approx. 1600 °C) during WAAM. Thus, a detrimental effect on the penetration behaviour and loss of strength of the concrete matrix is expected. This paper focusses on the heat propagation during WAAM and its potential effect on the paste rheology.

The results of the rheological measurements show that an application of both tested cement paste mixtures is possible for welding distances of approx. 62–68 mm and 82–84 mm to the particle-bed which reduce the temperature to 70 °C and 50 °C without additional cooling.

Keywords: Concrete · Additive Manufacturing · Particle-bed · 3D printing · Reinforcement · Selective paste intrusion · Wire and Arc Additive Manufacturing

1 Introduction

The 3D printing technology Selective Paste Intrusion (SPI) is a particle-bed based Additive Manufacturing technology, which deposits particles (aggregates 0.5–5 mm) in small layers (2–5 mm) and locally bonds them with a binder (cement paste). A major advantage of this technology compared to other AM processes is that support structures for cantilevers are not required. Furthermore, SPI objects achieved already high strength (>70 MPa) and durability (resistance to carbonation, freeze thaw and chloride attacks) [1–4].

However, to qualify SPI for the production of structural concrete elements, the inclusion of reinforcement is necessary. An innovative approach is to print the reinforcement simultaneously by employing Wire and Arc Additive Manufacturing (WAAM), see Fig. 1.

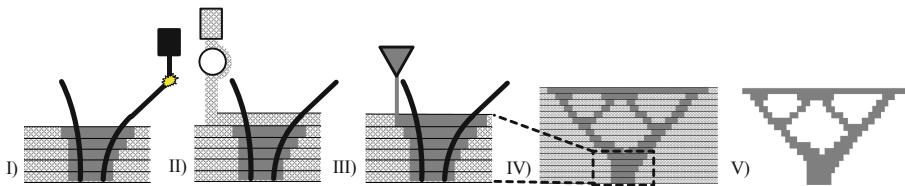


Fig. 1. Production cycle of SPI with WAAM manufactured reinforcement: I) Application of the WAAM reinforcement; II) spreading of the next aggregate layer; III) intrusion of the cement paste in the target layer (challenge of cement paste application below overhanging reinforcement will be considered); repeating of I–III until the object is finished (IV)

By using WAAM, a wire-shaped filler material is directly used as a wire electrode and continuously molten. WAAM offers high build-up rates (>50 g/min of steel) and is therefore especially suitable for fabrication of large-volume components. Since a few years ago, WAAM has been the subject of research for mechanical engineering applications [5–9]. A promising use case is the production of complex near net shape structures from titanium for aerospace applications, in order to increase material efficiency [10].

In comparison to other AM technologies, WAAM allows for building steel reinforcements layer by layer with a suitable geometrical complexity. Additionally, small layer heights (1–3 mm) and similar properties compared to those of construction steel can be achieved [11]. Hence, WAAM also proved to be suitable for printing pure steel structures [12, 13].

The major challenge that arises from the combination of WAAM and SPI is the occurrence of high temperatures (approx. up to 1600 °C) during WAAM. The high temperatures of the steel bar will cause increased temperatures of the particles in the particle-bed around the reinforced areas. Thus, a detrimental effect on the particles and the cement paste (penetration behaviour and loss of strength of the concrete matrix) is expected.

The focus of this paper is threefold: First, we analysed the impact of the increased temperatures on the rheological behaviour of two different cement pastes varying in type of cement and superplasticizer. Second, we determined the heat propagation within the rebar during the WAAM process depending on the welding time. Finally, we could indicate a minimum distance between the welding point and the particle-bed.

2 Materials and Methods

2.1 Materials

To investigate the effect of increased temperatures in the particle-bed on the rheological properties of the cement pastes we investigated two different mixtures both with w/c-ratio of 0.3. Mixture I consisted of an OPC (42.5 N, blaine: 2906 cm²/g) and a polycarboxylate ether-based superplasticizer PCE A (showing slow adsorption behaviour and liquefaction over time), whereas mixture II was blended from an OPC (42.5 R, blaine 3050 cm²/g) and a PCE B (faster absorbing than A with decreasing effectivity over time). Both mixtures were produced with deionized water within 180 s in a high intensive mixer with a break of 30 s after half the mixing time. All mixtures aimed at a slump flow after 15 min of 400 ± 5 mm and were adjusted only by the PCE content. Furthermore, to maintain the w/c-ratio of 0.3, the water content of the mixture was reduced by the water content of the superplasticizer. The designated temperatures (20 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C) of the mixtures were set by precooling or preheating the water and the cement. After mixing, the cement paste was stored at rest at the designated temperatures until the measurements began.

The wire electrode with a diameter of 1.2 mm for the Wire and Arc Additive Manufacturing process was made from G4Si1, which is a weldable construction steel. The substrate plate consisted of the construction steel S235JR. Carbon dioxide was used as an active shielding gas during welding.

2.2 Methods

For the rheological measurements, we used a rotational double-plate rheometer with a diameter of 50 mm and a roughened surface to prevent surface slip. The plates were adjusted to the designated temperatures (20 °C, 30 °C, 40 °C, 50 °C, 60 °C and 70 °C). The testing of the rheological properties was conducted 15 min after water addition. The test procedure consisted of a pre-shearing period of 30 s at a shear rate of 40 s⁻¹ and 19 descending steps from 80 s⁻¹ to 0.02 s⁻¹ each 6 s. The dynamic yield stress and the dynamic apparent viscosity were calculated using the Herschel-Bulkley model.

The WAAM system employed is based on Gas Metal Arc Welding (GMAW). Thereby, the wire electrode is placed dropwise on the substrate. The power source (CMT Advanced 4000 R from Fronius International GmbH) allowed the use of the Cold Metal Transfer Process (CMT). CMT belongs to the GMAW processes and is characterized by a pulsating wire feed, which enables a more targeted and concentrated energy input than conventional GMAW methods. A 6-axis industrial robot (KR15/2 from Kuka AG) was used to move the welding torch over the substrate. Type K mineral insulated thermocouples were used for temperature measurement.

Based on statistically designed experiments, the temperature distribution in a WAAM-built reinforcement was analysed. In preparation for this, three identical steel rebars were manufactured with constant process parameters (see Table 1) and in total 75 layers were deposited with a waiting time of $t_{\text{wait}} = 20$ s between each layer. These rebars provided identical initial conditions for the following temperature measurements. Three measuring cycles were performed on each rebar. The measuring cycles consisted of two welded layers with constant process parameters (see Table 1). After each measurement, the rebar cooled down (without coolant) to 23 °C in order to capture the inherent cooling rate. Figure 2 depicts the experimental set-up as well as the location of the measuring points (MP) along the specimen. Subsequently, at the MP the temperature over time on the surface of the rebar was determined.

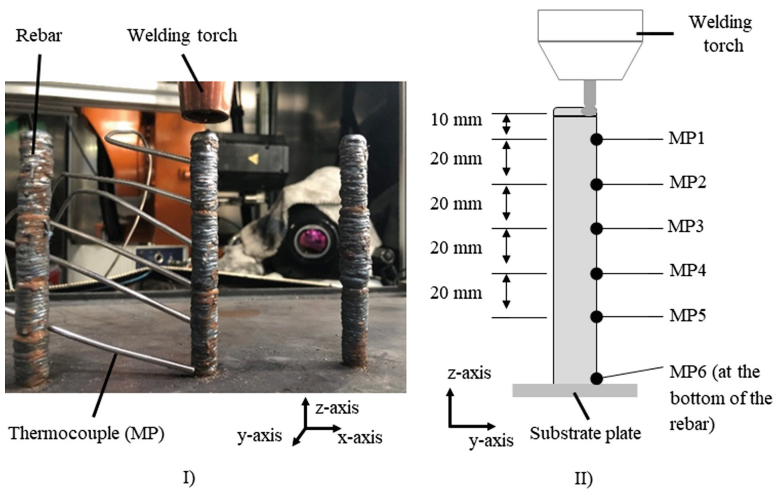


Fig. 2. Experimental set-up with sensors for the temperature measurement I) and overview of the defined measuring points II)

Table 1. Overview of process parameters held constant during the WAAM experiments

Symbol	Value and unit	Description
I	56 A	Welding current
U	19.1 V	Welding voltage
v_{TS}	250 mm/min	Traversing speed of the welding torch
v_{WFS}	1.6 m/min	Wire feed speed of the electrode
Q_{gTorch}	21 l/min	Volume flow of the shielding gas from the welding torch
d_{Wire}	1.2 mm	Diameter of the welding wire (electrode)
d_{rebar}	12 mm	Diameter of the rebar
δ	90°	Angle of the welding torch to the substrate
d_{Offset}	1.5 mm	Offset between every deposited layer

The influence of the waiting time between every deposited layer t_{wait} is decisive for the temperature distribution within the part. Therefore, t_{wait} was varied systematically for the three rebars (10 s, 20 s, and 30 s - full factorial plan with three steps and three repetitions).

3 Results and Discussion

3.1 Rheological Behaviour of the Cement Pastes

Figure 3 shows the development of the rheological properties of the cement pastes depending on the temperature of mixture I. Figure 4 shows the same for mixture II. Both mixtures showed a constant slump flow of 400 ± 15 mm over 180 min at 20 °C.

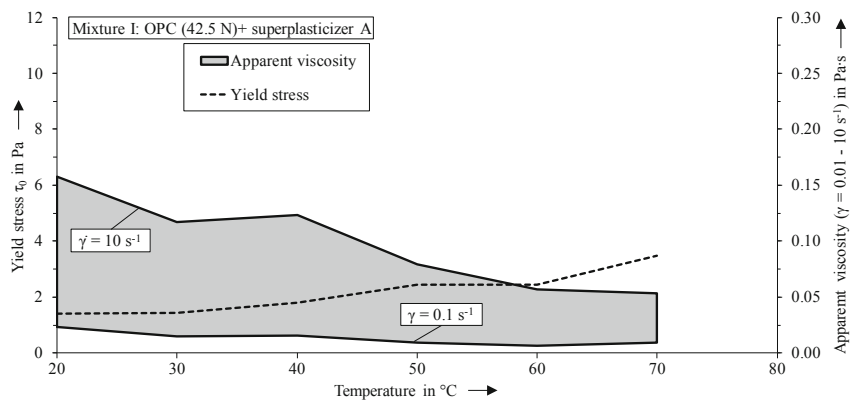


Fig. 3. Rheological properties of mixture I as a function of the paste temperature

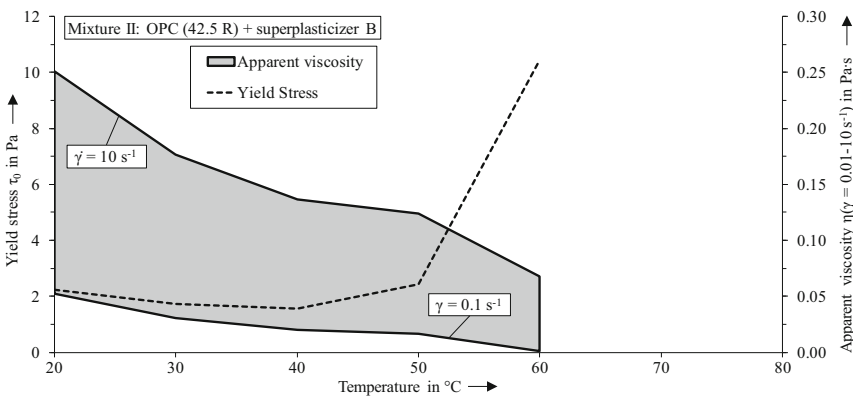


Fig. 4. Rheological properties of mixture II as a function of the paste temperature

In particular, Fig. 3 and Fig. 4 show the apparent viscosity at shear rates between 0.1 s^{-1} and 10 s^{-1} (grey area). These shear rates appear during the penetration of cement paste under gravity in a particle-bed [14, 15]. Along with the yield stress, the apparent viscosity is a decisive factor for the penetration behaviour of the cement paste particularly at slump flow values $\geq 350 \text{ mm}$ [15].

The measurements exhibit a decrease of the apparent viscosity for both mixtures between 20°C and 70°C . This is beneficial for the penetration ability of the cement paste in the particle-bed [15]. A possible explanation is the increasing adsorption behaviour of the superplasticizers with increasing temperature. A further reason can be found in [16, 17]. There, a decreased bonding force between the particles and an increased inter-particle distance explains this phenomenon.

The yield stress governs the penetration behaviour at slump flows $<350 \text{ mm}$, but is, besides the apparent viscosity, still a key factor for the penetration behaviour for $\geq 350 \text{ mm}$ [15, 18], which is valid for the cement pastes under investigation.

Mixture I shows a yield stress slightly increasing from 1.4 Pa at 20°C to 1.8 Pa at 40°C . At higher temperatures of 50°C and 70°C , the yield stress further increases slightly from 2.5 Pa to 3.5 Pa . In addition, the yield stress of mixture II grows exponentially from 2.4 Pa to 10.4 Pa in the temperature interval from 50°C to 60°C .

The increasing yield stress with increasing temperatures is assumingly caused by increased hydration kinetics. Presumably, early hydration products begin to grow and an arrangement of the cement particles starts [17, 19–21]. Furthermore, the faster consumption of the PCE B leads to a limited liquefying ability over time. Therefore, the hydration products could coat the adsorbed PCE on the cement particles' surfaces. This, in combination with the faster hydration kinetics of OPC (42.5 R), probably leads to the pronounced increase of the yield stress for temperatures over 50°C .

Simultaneously, the yield stress of mixture II decreases from 2.2 Pa to 1.6 Pa with increasing temperature up to 40°C . This is presumably caused by the faster adsorption behaviour of PCE B compared to PCE A. The authors of [16] explained this effect with an increase in the Brownian motion of the particles, which decreases the interaction between the agglomerates.

According to findings in [1, 2, 4, 15, 18], the yield stress of the cement paste should be $<3\text{--}6 \text{ Pa}$ to achieve sufficient penetration behaviour. This value depends on the grain size of the particle-bed ($d_{50} = 1.0 - 2.6 \text{ mm}$). Therefore, mixture I can be used for temperatures in the particle-bed of up to 70°C and mixture II works for particle-bed temperatures of up to 50°C . It has to be kept in mind that the evaporation of the water from the cement paste at increased temperatures has to be considered for the combination of SPI and WAAM.

3.2 Temperature Distribution of WAAM Rebars

Figure 5 shows the determined maximum temperature values at the surface of the rebars as a function of the distance to the welding point for $t_{\text{wait}} = 10 \text{ s}$, 20 s and 30 s . Figure 6 depicts the temperature profile at a distance $d_{\text{wp}} = 10 \text{ mm}$, 70 mm and 110 mm offset to the welding point as a function of the cooling time after the welding process for $t_{\text{wait}} = 10 \text{ s}$, 20 s and 30 s .

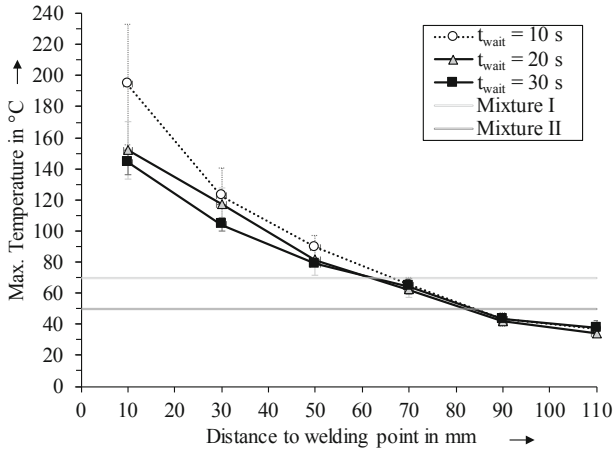


Fig. 5. Maximum temperature at the surface of the rebars as a function of the distance to the welding point for $t_{\text{wait}} = 10$ s, 20 s and 30 s

According to Fig. 5, the higher the distance between the measuring point and the welding point, the higher the temperature difference. Further the temperature decrease is exponential. This leads to a strong decrease in the temperature from the welding point to the first measurement point (10 mm). For a 10 s waiting time (break) between two layers the temperature decreases from approx. 1600 °C to 194 ± 39 °C, for a 20 s break to 152 ± 10 °C and to 144 ± 8 °C for a 30 s break. Additionally, these results indicate that the waiting time between two layers has a major influence on the maximum temperature on the surface of the rebar near to the welding point. Furthermore, the standard deviation of the maximum temperature values on the surface is high. This could be explained by the strong heat radiation originating from the welding point and the heat conduction through the rebar. However, the effect of the heat radiation is probably influenced by convective airflows as well as the active shielding gas from the welding torch around the rebar. Therefore, the deviation of the temperature decreases with increasing distance to the welding point due to the decreasing effect of the heat radiation (see also Fig. 6). This phenomenon should be further investigated by thermographic measurements.

In addition, the results exhibit a decreasing standard deviation of the maximum temperatures for the different waiting times with decreasing distance to the welding point, which is probably caused by the increasing contribution of the heat conduction through the rebar and a heat balancing due to the low thermal conductivity.

The rheological measurements for mixture I require a temperature <70 °C and for mixture II <50 °C. Without additional cooling, these results necessitated distances to the welding point of at least 62 mm to 66 mm for mixture I and of 82 mm to 84 mm for mixture II (dependent on the waiting time). In practice, these distances require great efforts for realisation in the production process.

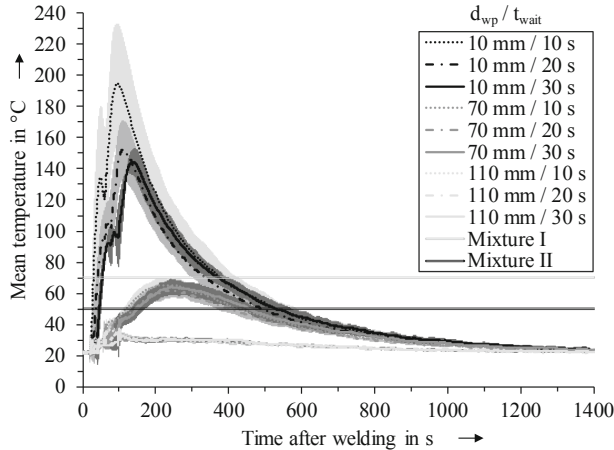


Fig. 6. Temperature distribution on the rebars' surfaces depending on the time after welding, the distances to the welding point $d_{wp} = 10$ mm, 70 mm, and 110 mm for $t_{wait} = 10$ s, 20 s and 30 s

Figure 6 shows the maximum temperature and the time until the rebar cools down to room temperature for each of the three t_{wait} . The temperature peaks for each t_{wait} decrease with increasing distance to the welding point. This is caused by the decreasing influence of the heat radiation. Simultaneously, the applied energy input is conducted through the rebar. Thus, the temperature peak of greater welding distances develops with a delay.

These results show that even lower distances from the welding point (e.g. 10 mm) to the particle-bed lead to temperatures that enable the use of mixture I and II. However, the waiting time for the application of the next layers results in an impractical long waiting time (>400 s for mixture I and >520 s for mixture II). Furthermore, the effect of the high temperatures in the particle-bed and the cooling ability of the particles in the particle-bed have to be investigated.

4 Conclusions and Outlook

This paper shows I) the impact of the increased temperatures on the rheological behaviour of two different cement pastes and II) the heat propagation within the rebar during the WAAM process in dependency of the waiting time between the welding of two layers in a combination with the process of selective paste intrusion. We could achieve the following main results:

- Both cement paste mixtures can be used up to a temperature of 50 °C with sufficient rheological properties with only slight increase in yield stress up to 2.5 Pa.
- Mixture I was even usable up to 70 °C with a yield stress of 3.5 Pa.
- The apparent viscosity between 0.1 s^{-1} and 10 s^{-1} decreased for both mixtures with increasing temperatures up to 70 °C, which is advantageous for the penetration behaviour.

- The temperature values of 50 °C and 70 °C are not significantly affected by the waiting time between the deposited layers.
- Between the welding point and the particle-bed a space of at least 62 to 66 mm for mixture I (70 °C) and 82 to 84 mm for mixture II (50 °C) is recommended. This ensures adequate temperatures in the particle-bed and therefore sufficient penetration behaviour of the cement paste.

We can conclude that a combination of SPI and WAAM to fabricate 3D reinforced additively manufactured structures is feasible and very promising. The results of this paper give proof of concept for a combination of the combined two manufacturing methods.

However, the strength of the reinforcement has not been determined yet. This is very important as it is highly relevant for the application. Therefore, research regarding material and process correlations are required. Furthermore, the evaporation of the water within the cement paste at high temperatures can have an impact on the characteristics of strength and durability.

The cooling without explicit cooling strategies of the rebars between deposited layers is time consuming. Great distances between the welding point and the particle-bed seem to be difficult to realise in a combined SPI and WAAM printer. Thus, the design of new materials as well as material combinations and the implementation of different cooling as well as water storing strategies has to be part of further investigations.

Acknowledgements. We express our gratitude to the German Research Foundation (DFG) for the funding of our research. The content of this paper was achieved within the scope of the research project “Particle-Bed 3D Printing by Selective Cement Paste Intrusion (SPI) - Particle Surface Functionalisation, Particle Synthesis and Integration of WAAM Reinforcement”, which is part of the Transregio TRR 277.

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Knitting Concrete

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Abstract. Due to concrete's traditional role as a casting material its appearance as a uniform solid mass is one of the material's most distinct traits. When poured in a mould fresh concrete adheres to the shape of the formwork and material distribution is not adaptable at a more detailed level. This paper explores how deposition-based additive manufacturing opens up new opportunities for controlling the distribution of concrete at a previously neglected intermediate scale - the meso-scale. By adopting principles of knitting to toolpath planning, the paper presents a computational method for varying the density, porosity, and surface articulation of the material, previously inconceivable due to the limitations of formwork.

Keywords: Additive manufacturing · 3D printing · Toolpath generation · Knitting · Material structures · Material scales

1 Introduction

In its traditional role as a cast material, the use of concrete in the built environment is fundamentally conditioned by the inverted relationship that exist between the material and formwork. Any work of cast concrete is essentially the positive imprint of a negative mould, and as the historian Peter Collins remarked, ‘To design a concrete structure is to design the formwork’ [1]. When poured in a mould, fresh concrete adopts the shape of its container, and at surface level, the impact of the mould remains visible in the imprint left by the surface character of the opposing formwork. As a result, concrete's appearance as a uniform solid mass is one of its most distinct traits.

The process of shaping concrete by deposition signifies a fundamental departure from existing formwork-based techniques. Instead of being shaped by the constraint and control imposed by a static mould, the material is deposited along a programmable path, performed by a numerically controlled machine. The former singular operation of the “pour” is replaced with a dynamic “choreographed flow”, in which the role of the line shifts from representing the perimeter of form to constituting the path along which the material “performs”.

Advantages of this emerging form of concrete manufacturing have so far been explored in the form of non-standard building components [2], the integration of services [3] and hollow wall typologies [4]. Yet, an overview of research in the field reveals a strong focus on technical feasibility with relatively few projects addressing added value in terms of design applications [5]. This project aims to contribute to counteracting this tendency by focusing on a relatively unexplored advantage of the

additive process, namely, its potential for achieving diverse and enhanced surface qualities. Compared to casting in a mould, that results in massive structures, the precision offered by additive manufacturing opens up the possibility of introducing local variations in the build-up of the material that can be exploited to achieve intricate, porous, and lightweight structures, previously unfeasible due to the limitations of the mould. For this purpose, we present a method for expanding the scope of design to the material's visible meso-structure (10^{-2} – 10^0 m) by controlling the distribution of the material at the scale of the deposited filament through the programming of toolpaths.

The rest of the paper is divided into four main parts. Firstly, we discuss specific design conditions for concrete deposition. Secondly, we present a method for integrating toolpath generation in the design phase by taking inspiration from the traditional craft of knitting. Thirdly, we demonstrate the applicability of the method in a series of prototypes at different scales. Lastly, we provide a concluding discussion about future potential of the approach.

2 Design for Concrete Deposition

It is commonly stated about additive manufacturing (AM) that any shape that can be imagined and drawn in CAD can be fabricated as a physical object. It has even been suggested that the unprecedented design freedom afforded by AM by now surpasses the abilities of CAD [6]. Geometric freedom is made-possible by the layer-by-layer procedure in which material can be precisely placed according to numerical values.

Under the popular term 3D printing, additive manufacturing has become widely known for turning digital files into physical replicas. However, the scaling-up of this fabrication process, that was initially intended for rapid prototyping, to full-scale construction, reveals discrepancies that raises questions about the appropriateness of conceiving of concrete deposition as a merely a scaled-up 3D printing process.

Despite widely claimed “geometric freedom”, concrete deposition, like any manufacturing process, imposes its own set of formal and material constraints. The dimension of the nozzle determines the level of detail and accuracy and without the use of external material support, formal features in the form of cantilevers are restricted to the ability of offsetting stacked layers to create overhangs. Moreover, the viscous nature of fresh concrete makes it difficult to start and stop the flow of material with high precision and the best results are therefore typically achieved by planning for continuous extrusion.

This paper specifically addresses two related challenges of scaling-up additive manufacturing to full-scale concrete deposition. Firstly, the implications for what is commonly referred to as “resolution” or “conformity to design”, and secondly, inherent limitations of a standard AM workflow for exploiting the full potential of the additive process.

2.1 Manufacturing Resolution

In a standard AM workflow, machine instructions are typically generated by a so-called “slicing” operation that divides a digital model into layers according to a specified layer

height. In the field, the level of detail to which a manufactured object corresponds to its digital counterpart, or so called “conformity to design geometry”, is typically referred to as “resolution”. The level of detail attainable is primarily determined by the thickness of the layers in the build-up of the material, which in turn, relates to the specific material process used. At layer heights around 20 μ , the stratified material structure becomes invisible to the naked eye. Conversely, concrete deposition typically operates at resolutions around 10,000–20,000 μ .

The reason for this is twofold. The size of the particles in the concrete mix determines the minimum nozzle diameter required in order to extrude material without blockage. Another reason relates to manufacturing speed. When scaling up build volumes to construction scale, the number of layers required to achieve the level of resolution commonly associated with AM exponentially increases and production time is not likely to be achieved within an acceptable time frame. This conflict between resolution and build time has been illustrated by the so called ‘resolution/deposition rate paradox’ [7].

Consequently, concrete additive manufacturing results in a layered material structure that is clearly visible and becomes the most predominant feature of the surface quality of the final result. Attempts to overcome this seemingly unavoidable side-effect have given rise to amending measures such as installing an integrated trowel tool that smooths out the surface as material is being deposited [8], changing the shape of the printing nozzle [9] and post processing in which a layer of mortar is applied over the rough surface [2].

2.2 CAD/CAM

Because both CAD and CAM are computer-based methods, it is possible for the processes of design and manufacture to be highly integrated (CAD/CAM). In a standard AM workflow, a CAD model is first exported as a triangulated mesh model (STL) that can be processed by a slicing program to be divided into toolpaths and exported as machine instructions in the form of G-code. Although highly integrated, this workflow still assumes a fundamental separation between design and manufacturing in that the scope of design is restricted to the overall geometry (macro scale) of the element to be manufactured, while the toolpath is defined by slicer algorithms normally outside of the reach of the architect.

It also follows that only what can be represented as a CAD model, can be manufactured. As most 3D modelling software use boundary representation modelling (B-rep) to mathematically represent solid geometry, a 3D model typically only represents the perimeter of form. In the slicing program, this boundary surface is converted into contour lines, and in the process small details will be lost due to the inherent resolution threshold. In order to achieve solid outcomes additional space filling toolpaths must be generated. An inherent limitation of boundary representation modelling thus resides in representing solids merely as shell geometry without specifying any internal structure.

The impact of toolpath planning on precision, build time, and mechanical and functional properties makes it central in all forms of deposition-based manufacturing. In prototype manufacturing research on toolpath strategies have demonstrated the possibility to functionally grade material by exploring the relationship between

microstructures and material properties [10]. New developments in toolpath generation have also given rise to a new sub-field related to so-called “freeform” [11], or “spatial printing”, that demonstrate the potential of moving beyond the conventional layering of material to achieve space-frame type structures [12]. Some recent experiments have extended this approach to clay, exploiting the viscous properties of the material to achieve mesh-like structures [13]. In large-scale concrete additive manufacturing non-conventional toolpath planning have been applied in projects that deposit material on non-planar substrate [14, 15].

3 Knitting – A New Approach for Concrete Deposition

As an alternative to the standard toolpath planning in AM, in which surfaces are created through the stacking of contour lines, our project looked outside the field of digital manufacturing for techniques to expand the range of design features made possible by the additive process. For this purpose, we turned to the craft of knitting - a technique with a long tradition in turning a continuous length of filament into complex material structures. While the craft of knitting and concrete construction might be considered worlds apart, potential for synergies have already been demonstrated in the form of custom-made knitted textiles used as lightweight stay-in-place formwork [16]. This project represents a different approach that draws on principles of knitting for concrete deposition. Robotic motion is correlated with the distribution of extruded material to infuse structure and surface variation to a hitherto uniform material.

3.1 Principles of Knitting

The use of knitting techniques to achieve complex and patterned textile forms has been utilized for centuries [17]. The inherent variability of its intermeshed loop structure offers great flexibility in forming different stitches that can be repeated and adopted across a continuous surface to form different knitted patterns. The further ability for knitted patterns to create advanced topological shapes is achieved by employing simple stitch operations during the progressively built-up from row after row of intermeshed loops. With the advent of machine knitting, the gesture of the hand movement involved in the different stitches is replaced with mechanical motion in order to convert yarn into knitted loop structures. Akin to additive manufacturing, machine knitting relies on little user intervention during the fabrication process, but rather in the precision in the execution of the programming of these machines.

3.2 Toolpath Generation

Instead of distinguishing between boundary curves and infill curves in toolpath planning, we propose a toolpath strategy based on programming motion patterns to arrange a continuous flow of material into intricate material structures. Drawing on principles of knitting, this procedural approach is designed as a succession of stitches that can be modulated according to local requirements. Similar to how stitches constitute the basic unit in a knitted textile pattern, the concept of the stitch here represents the building

block of the toolpath. A stitch is defined as a sequence of control points within a coordinate system, and programmed and sequenced along a linear trajectory to create one continuous path.

To integrate toolpath generation in the design phase, our current implementation uses a workflow in the Grasshopper® environment within Rhino®, based on scripts written in Python. Four main steps are involved in the generation of the toolpath: (i) slicing a model to generate reference lines, (ii) sequencing stitches along those lines according to specified parameters, (iii) visualize the outcome in the CAD environment to evaluate the need for further optimization, (iv) export the toolpath as G-code or robotic programming languages using third party add-ons.

The sequence of stitches is executed by an algorithm that procedurally generates stitches along the base curve obtained from the slicing operation through the following operations: divide the base curve into nodes according to a defined wavelength, create a local coordinate system for each node based on the tangent and normal vector for each node. Then, a set of control points is created in the coordinate system for each node, according to the parameters and the programmed sequence of stitches. Finally, a single NURBS curve is interpolated through this sequence of control points to constitute the toolpath.

By specifying different parameters to the stitches, the resulting pattern can be adapted across the model to respond to variable requirements. The same approach is then replicated along the vertical axis to every layer and combined in one continuous toolpath (Fig. 1).

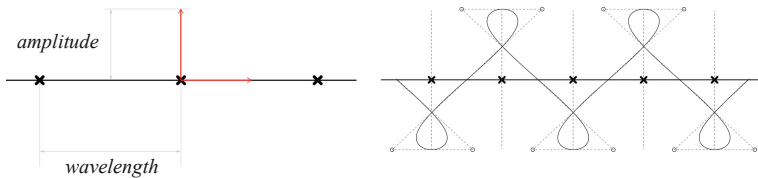


Fig. 1. Toolpath generation algorithm

4 Experimental Procedure

To evaluate the potential of the proposed method to expand the range of possible surface qualities in additive manufacturing, the experimental procedure involved prototyping of generated patterns in different materials and scales. When working with non-standard toolpaths, prototyping becomes essential to the design process in order to predict material behaviour under specific circumstances, which would be impossible to prescribe as a conventional 3D model.

The aggregation of stitches produces patterns that can be applied and adapted to any geometry. At the core of this approach lies the hypothesis that the additive process itself can be used to introduce material complexity at the meso-scale which is out of reach of standard CAD modelling procedures. Hence, a basic block shape was chosen as a test object, to emphasise the variation of possible outcomes within the boundary

condition of a standard object. The test object is comparable to what in knitting practice is referred to as a pattern “swatch” i.e. the sequence of stitches that makes up a sample of knitted pattern. Within this project, the swatch object serves as a suitable standard format to evaluate pattern types based of different stitches and their associated features.

4.1 Material Test Path

The non-standard nature of the toolpaths at-hand exploit an expanded range of material behaviour, exemplified by integrated features such as folding and bridging. Correlations between robotic motion and material behaviour therefore had to be established. For this purpose, a specially designed toolpath was developed to simulate material operations and generate relevant data of the material behavior of different concrete mixes. Unsupported material extrusion (bridging) was found to be feasible without significant deformation within shorter spans (<2 cm) while spans up to 8 cm were achievable without breaking, but with significant deformation in the form of sagging (Fig. 2).

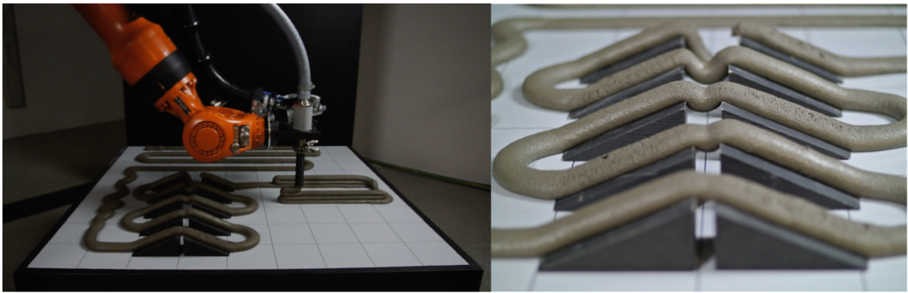


Fig. 2. Experimental setup at KTH School of Architecture. Robotic concrete deposition tool with a 20 mm diameter nozzle.

4.2 From Stitch to Pattern

Beyond the simple stacking of stitches, operations such as amplitude modulation, phase modulation and flipping the normal, were introduced in the aggregation of stitches into patterns to explore emerging surface features. From an early application of the method with sine-like stitches, the following basic observations could be made: the progressive increasing of amplitude creates a cantilevering effect, a decreasing amplitude value results in a recessing effect, phase modulation shifts a pattern along the base curve, while flipping the normal can generate alternating patterns that create the same surface qualities on both sides. With our toolpath generation script multiple modulations can be applied at the same time and extended to other stitches (Fig. 3).

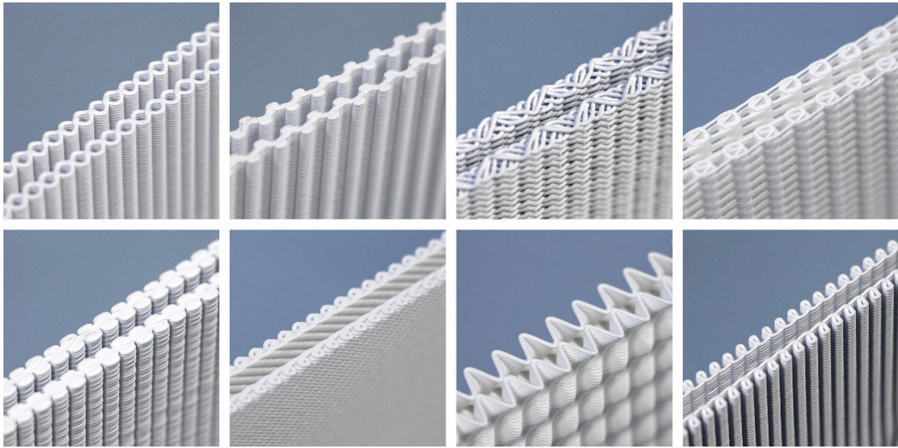


Fig. 3. Selection of generated patterns from simple sine- and looping stitches. Manufactured with a 0.8 mm diameter nozzle using a Ultimaker 2+ FDM printer.

4.3 Full-Scale Prototypes

To prove the scalability of the approach to concrete manufacturing, five of the previous patterns were reproduced at full-scale by XtreeE in Paris (Fig. 4).



Fig. 4. Full-scale prototypes of generated patterns. Manufactured by XtreeE. Photo by XtreeE.

4.4 Stitch Sampler

To expand the range of possible patterns, a generative scripting tool was set up to automate the full generation of stitch types (the probability space) from a constrained set of control points. Given the procedural nature of the algorithm, we predefined a set of control points in order to iterate through all the possible combinations to generate a vast sample of possible stitches. Not all synthetic stitches may constitute valid tool-paths. Further analysis can aid the sorting of the generated sample space according to optimised uses. From now on, stitch types can be searched and reproduced according to the control points sequence that generates them (Fig. 5).

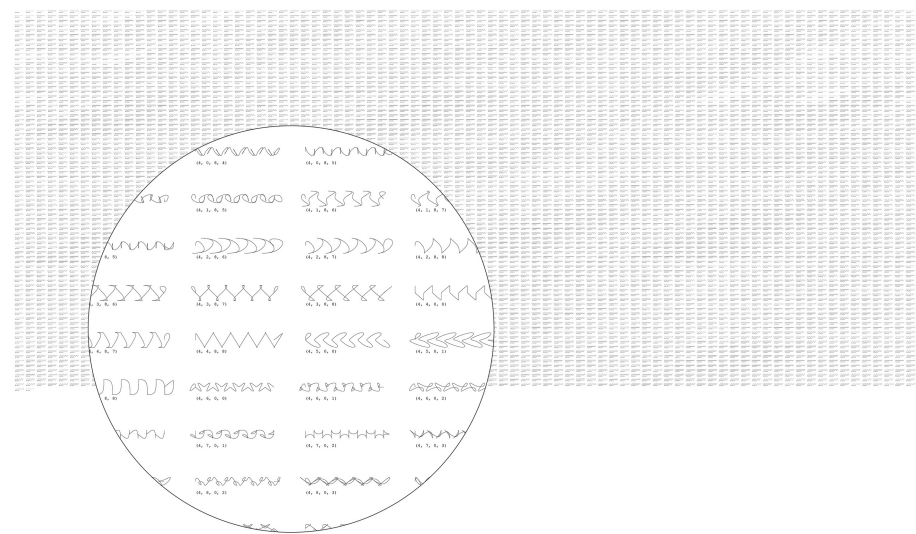


Fig. 5. Generated sample space of 6561 stitches using a sequence of four control points for each node.

4.5 Pattern Switch Library

Following the aggregative operations as already outlined in Sect. 4.2, an expanded range of patterns were generated from a selection of stitches and compiled in a library of pattern switches (Fig. 6).

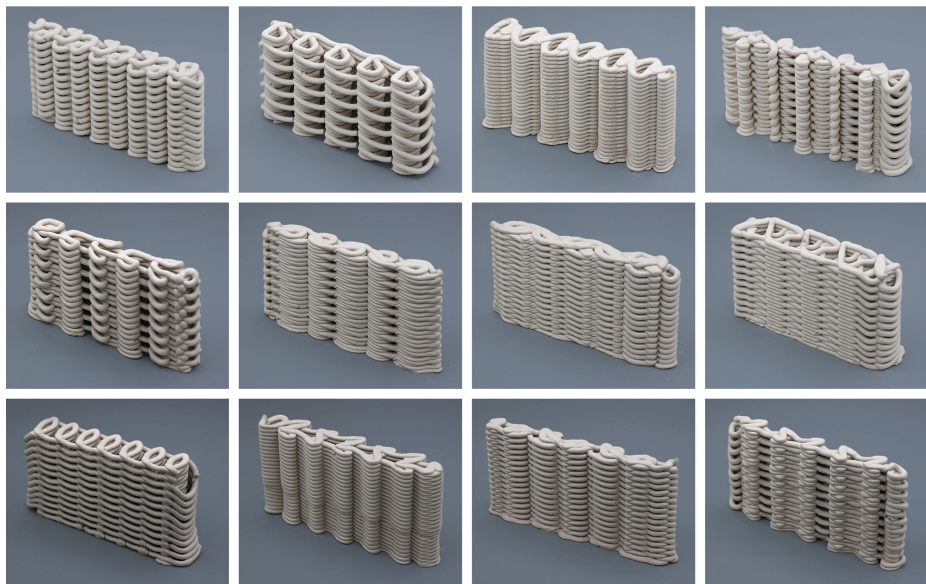


Fig. 6. Selection of patterns. Prototypes fabricated in clay with Delta WASP 3MT printer with a 6 mm nozzle.

5 Discussion and Conclusion

This paper has aimed to demonstrate the potential of adopting principles of knitting in toolpath generation for concrete deposition. The proposed method, based on controlling the local geometry of the toolpath itself and the effects of aggregation through the controlled modulation and accumulation of stitches, provides new means of varying the density, porosity and surface articulation of concrete.

The objective has not been to deliver a single most efficient toolpath solution, but rather to demonstrate the range of possibilities by this method. The paper has further demonstrated the compatibility of how the integration of the procedural generation of the toolpaths in the early stages of the design, can be applied as a way of incorporating design at the meso-scale as part of the tool palette available to architects and designers.

The ongoing goal of the project is to build up a library of three-dimensional patterns that can automatically be applied to concrete design. This library will form the basis for future research relating to the potential of this approach for applications involving optimized material use, minimising the self-weight of building components, and maximizing thermal and acoustic performance.

Acknowledgements. The work presented in this article was partially funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 642877.

The authors would like to thank XtreeE for their generous support and expertise in the production of full-scale prototypes. The authors also thank colleagues at RISE Research Institutes of Sweden who provided insight that greatly assisted the research.

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Concrete 3D Printing: System Development, Process Planning and Experimental Results

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Abstract. Concrete 3D printing is a new construction technology that deposits the concrete from the bottom up layer by layer. The printer and process used in this technology are different from traditional extrusion-based printing technology. This work developed a concrete 3D printing system and its process planning from the point of considering the “large-scale” of the printer and the thixotropy of the concrete. Firstly, the components of the printer were introduced, and the screw as the key part of the extruder subsystem was optimized based on ANSYS Fluent. Secondly, the key technical problems in the process of tool path generation and parameter design were discussed. Lastly, the feasibility of the concrete 3D printing system and process planning were verified by a pavilion printing experiment.

Keywords: Concrete 3D printing · System development · Process planning · Tool path generation

1 Introduction

Concrete 3D printing is a digital and automated construction technology, which creates a building by adding cement-based materials from the bottom up layer by layer. Compared to conventional construction technology, concrete 3D printing can simplify the construction process and improve efficiency because it does not require formwork. Therefore, concrete 3D printing technology has wide application prospects in the field of architecture. The research on concrete 3D printing mainly includes the development of printing equipment, the development of cement-based materials and the printing process planning. There are three printing ways: (i) Printing the whole building on site [1]. (ii) Printing smaller blocks of pre-fabricated elements and assemble them together to form a larger object [2]. (iii) Multi-robots collaborative printing [3]. For large-scale

mechanical structures, there are three common types: gantry structure [4], cable-suspended robot [5] and robot arm [6, 7]. The gantry structure has high stability, accuracy and bearing capacity, but the size of construction is limited by machinery [8]. Cable-suspended robots are relatively inexpensive and are easy to transport, disassemble and reassemble. But the control of cable robot is difficult, and it is easy for robot to collide with the structure under construction [9]. The robot arm is easy to carry to construction site. But the range of motion of the manipulator is limited and some positions can't be reached directly [10].

Concrete is a composite material consisting mainly of cementitious materials and cement aggregates. Unlike ordinary concrete, concrete used for 3D printing must have good pumpability, extrudability, and buildability [11]. The corresponding feeding system must be designed to mix the concrete evenly and then pump it to the printer. Thixotropy is an important characteristic of concrete, so pumping and extrusion must take into account the influence of shear force on the properties of fresh concrete [12]. The research on rheological behavior of concrete can provide theoretical basis for the development and optimization of pumping system of 3D printing system [13, 14]. Temperature also has a great influence on the performance of fresh concrete. Heating can improve the shape stability of fresh concrete [15].

The key of concrete 3D printing is to accurately extrude the high property concrete on the right path at the right time. In order to get high structural strength and good appearance of printed buildings, these points must be achieved: (i) High positioning accuracy of the system; (ii) Good fluidity and constructability of materials [16]; (iii) Appropriate tool path setting. However, most researchers only focus on one aspect of concrete 3D printing, without systematic development and process planning. Each part of concrete 3D printing system and process will affect the quality of printing, so each part must be developed according to the characteristics of concrete 3D printing [17].

2 System Development

Concrete 3D printing system consists of mechanical subsystem, control and driving subsystem, feeding subsystem and extrusion subsystem, as shown in Fig. 1. Mechanical subsystem is mainly the framework to support printer. The control and driving subsystem is responsible for controlling the movement of printer mechanism and the extrusion of concrete by coupling control of motor. Feeding and extrusion subsystem includes concrete mixer, peristaltic pump and extrusion mechanism, which is responsible for transporting concrete to the end of nozzle.

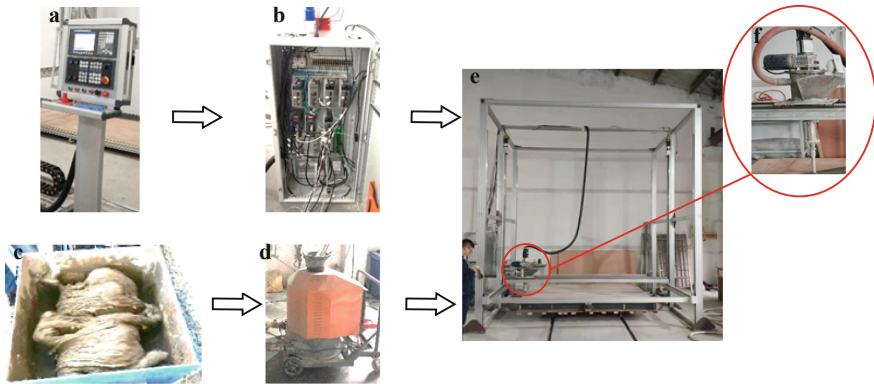


Fig. 1. Concrete 3D printing system. (a) Control subsystem; (b) Driving subsystem; (c) Mixer; (d) Peristaltic pump; (e) Mechanical subsystem; (f) Extrusion subsystem.

The direct connection of the nozzle to the pumping pipe will cause certain pulse and delay in the pumping of the concrete through a long pipe, which will affect the printing. In order to reduce the delay of concrete extrusion and improve the uniformity of concrete filament in the printing process, the extrusion subsystem is designed for extruding the concrete from the hopper to the end of the nozzle and depositing it on the print platform. The extrusion subsystem is important and it must satisfy the following conditions: (i) Fast response; (ii) Extrusion speed can be adjusted. (iii) The continuity and uniformity of concrete supply must be maintained in the printing process [18]. (iv) The flow pulse of extruded concrete is small. To meet the above requirements, an extrusion system consisting of concrete hopper, mixing blades, screw, rotating mechanism (for square or rectangular nozzle that needs changing orientation during printing) and nozzle is designed, as shown in Fig. 2.

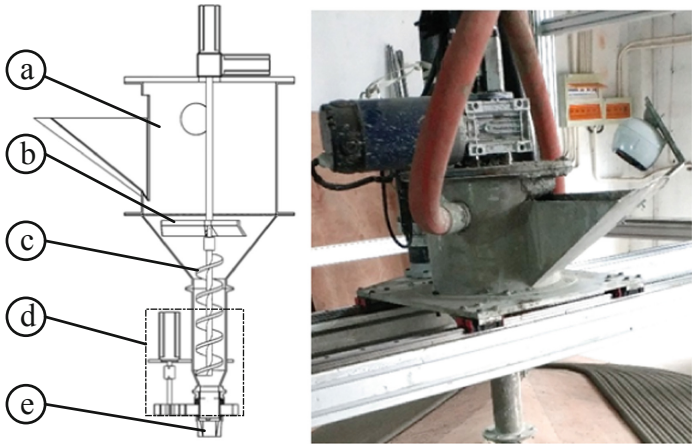


Fig. 2. Extrusion subsystem. (a) Material hopper; (b) Mixing blades; (c) Screw; (d) Rotating mechanism; (e) Nozzle.

Screw is responsible for extruding concrete from hopper to the print platform, and provides axial thrust by rotating. Screw design has significant influence on the extrusion pressure, velocity and efficiency, further the quality of the printed objects. ANSYS Fluent was used to analyze the fluid structure coupling of the concrete mortar in the sleeve. Set the material properties to Bingham fluid, incompressible fluid, and laminar flow fluid. The Herschei-bulkley model was selected and the material parameters are shown in Table 1. The area around the screw is set as a moving fluid area. The rest of the area is set as a static fluid area, while the screw is suppressed. A rotation velocity is given to simulate the rotation of the screw.

Table 1. Material parameters setting of Herschei-bulkley model in ANSYS Fluent.

Density	Consistency index k	Power law exponent n	Yield stress threshold τ_0	Yield viscosity μ_0
1900 kg/m ³	30	0.6	110	35

The design parameters of screw affect the extrusion pressure. In addition, the diameter of the sleeve and the nozzle angle affect the extrusion efficiency. Figure 3a shows that there is a conical “dead zone” with a material velocity of zero around the sleeve outlet (causing the materials to accumulate at the outlet). Therefore, the nozzle angle was optimized to 135° according to the simulation analysis. The concrete in the sleeve is in flowing state and the concrete mortar in the sleeve has obvious velocity gradient, which shows that the screw has obvious shear and mixing effect on the material, as shown in Fig. 3b. The pressure of the screw toward the output end is obviously greater than the pressure of the back blade, indicating that the screw has a pushing effect on the concrete mortar, as shown in Fig. 3c. The screw is fixed by the input end bearing and suspended by the output end. The shape variable of the output end is far less than the distance between the screw blade and the cylinder wall, as shown in Fig. 3d.

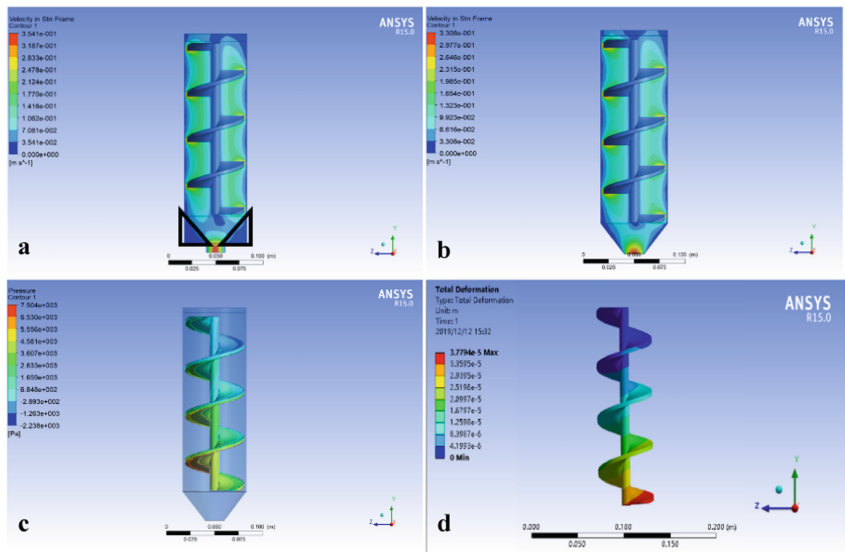


Fig. 3. Fluid solid coupling analysis of screw and concrete. (a) “Dead zone” of flow; (b) Concrete velocity; (c) Pressure on extrusion screw; (d) Deformation of extrusion screw.

3 Process Planning

Process planning refers to the whole printing process from raw material input to finished product output through concrete 3D printing equipment including: (i) material preparation and feeding process; (ii) model design, slicing and tool path generation; (iii) process parameter design, as shown in Fig. 4.

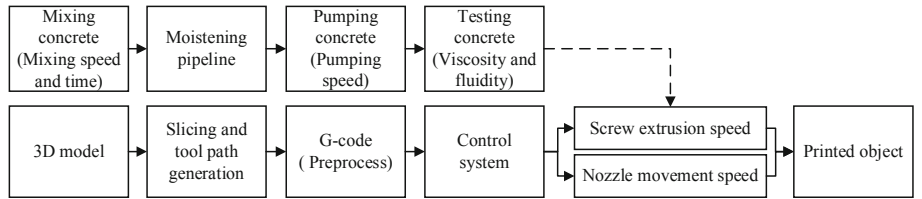


Fig. 4. Concrete 3D printing process planning flow

3.1 Tool Path Generation

There are large differences between fused deposition modeling 3D printing and concrete 3D printing: (i) The ratio of model size to single filament size is different, namely the ratio of traditional 3D printing model is very large, while the ratio of concrete is small. (ii) The material properties of concrete differ greatly from those of molten materials. (iii) Concrete does not need to be heated during printing. Therefore,

conventional slicer doesn't apply to concrete 3D printing. This work develops a G-code generation plug-in for concrete 3D printing, which can freely edit the tool path and change the control parameters in the printing process.

The strength of building structure must be taken into account in generating tool paths for 3D printing of concrete. In order to ensure the bonding strength, more extrusion must be carried out at the intersection. However, too much extrusion will lead to the accumulation and protrusion of concrete materials, which will affect the appearance of the building. Extrusion works particularly well when it is done continuously, but problems such as over-printing (too much material deposited) arise when the material flow is interrupted and under-printing (a pause in deposition that doesn't coincide with nozzle movement) when re-starting. Therefore, the printing path should be as continuous as possible to reduce the starting and stopping frequency of extrusion screw. Figure 5 depicts the G-code generation strategy of tool path.

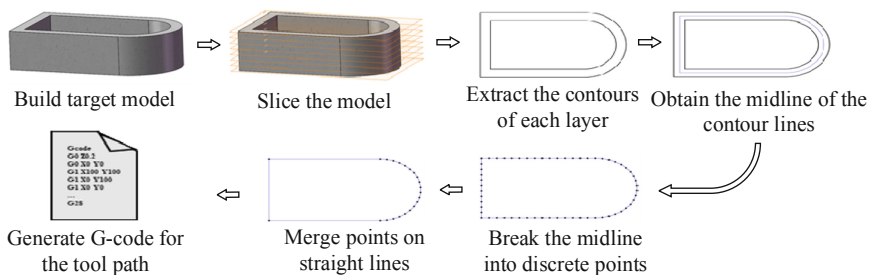


Fig. 5. G-code generation strategy of tool path for concrete 3D printing

3.2 Process Parameter Design

The process parameters of concrete printing are closely related to the performance characteristics of the final product [19]. The design of process parameters includes materials mixing speed, materials mixing time, materials pumping speed, printing layer thickness, screw extrusion speed and nozzle moving speed. Specifically, the materials mixing speed and mixing time have important effects on the materials fluidity, the materials performance and the printing efficiency. The material pumping speed determines the initial pressure of the screw, and then affects the extrusion quality. Therefore, it is necessary to ensure that the materials in the hopper is constant by controlling the material pumping speed. The printing layer thickness is a main factor affecting the printing accuracy. The smaller the layer thickness, the higher the accuracy, the more layers and the more time is spent in the printing process. The maximum number of printable layers is determined by the material properties and the printing layer thickness.

The control of extruder motor speed directly affects the quality of extrusion filament. In order to explore the relationship between the motor speed and the materials flow rate at the outlet of the nozzle, the materials flow in the sleeve under different motor speeds of the extruder was simulated. The simulation results are shown in

Fig. 6a and the black dashed indicates the materials backflow areas. The corresponding nozzle outlet flow at different speeds of the extrusion motor was recorded. As shown in Fig. 6b, the blue line represents the theoretical results when the materials are extruded only along the axial direction, and the yellow line represents the simulation results under the composite motion of the materials. The two variables are approximately proportional in both situations.

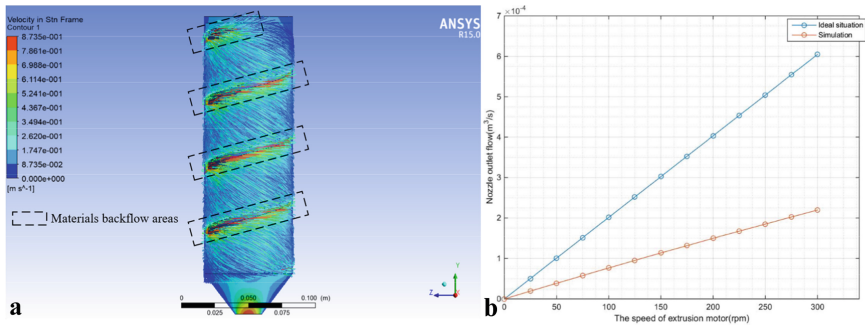


Fig. 6. Simulation of the motor speed and nozzle outlet flow. (a) The black dashed indicates the materials backflow areas; (b) The motor speed and nozzle outlet flow are proportional.

4 Experiments

4.1 Preliminary Experiment

The purpose of the preliminary experiment is to determine the ratio of extrusion and printing speed. The width and quality of the filaments are influenced not only by material characteristics, but also by extrusion rate and nozzle movement rate. In order to extrude layers of uniform thickness, the extrusion speed must be matched to the moving speed of the nozzle. In theory, $w = Q/(v * h)$, where w (mm) is the print width, h (mm) is the height of the layer, v (mm/s) is the moving speed of the nozzle. Q (ml/s) is the flow rate of the concrete through the nozzle, which is controlled by the speed of the extrusion motor [20]. When the material properties and the height h of the layer remain unchanged, w can be observed to change with the ratio of Q to v . A circular nozzle with a diameter of 30 mm is used in the experiment. Three groups of experiments are designed to determine the appropriate ratio of extrusion speed to nozzle moving speed. The moving speed of nozzles used in the three groups of experiments is different. By measuring the width of concrete and taking the average values of three groups of experiments, the appropriate ratio is finally obtained, as shown in Fig. 7.

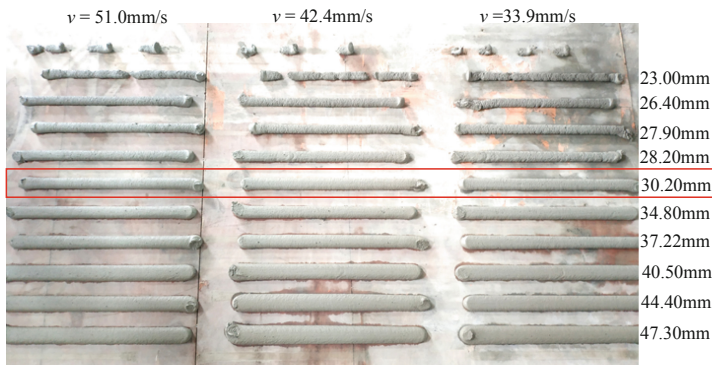


Fig. 7. Variation of width of filament with the ratio of extrusion and printing speed

4.2 A Pavilion Printing Experiment

Model Design

The design of concrete 3D printing model is directly related to a series of core issues, such as whether the model can be printed, the structural strength of the model and the installation. The wall of the pavilion is hollow and has internal structures. The wall is composed of external contour and stiffener. Insulation or sound insulation materials can be added to the hollow structure of the wall to increase the insulation or sound insulation performance of the pavilion. In order to improve the structural strength and seismic performance of the pavilion, four columns are reserved in the wall for inserting reinforcing bars and pouring concrete. The roof must be built with sacrificial support, so the model is divided into two parts: the wall and the roof. Finally, a pavilion of 2.5 m * 2.5 m * 3 m size is designed, as shown in Fig. 8.

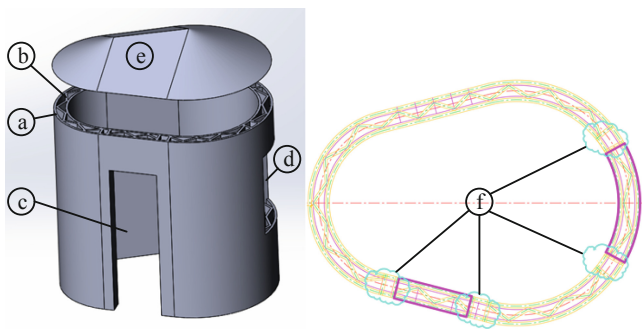


Fig. 8. CAD model of the pavilion. (a) Wall contour; (b) Stiffener; (c) Door; (d) Window; (e) Roof; (f) Reserved columns for inserting stiffener and pouring concrete.

Wall Printing

The wall is printed on a steel frame base with two tracks for movement, as shown in Fig. 9. The base and the wall are connected by concrete poured with steel bars. The path planning method of the slicing software is to traverse the path completely, and the print path of the same layer can't overlap. In addition, concrete has poor fluidity and bonding capacity at track intersection. Therefore, the wall is divided into the outer contour part and the stiffener part as shown in Fig. 9a, and the two parts need to be embedded at the intersection point to ensure sufficient bonding strength.

In each layer, the contour is printed first and then print the stiffener. After the contour is printed, the strength of concrete increases with time. When printing stiffeners, the contour part has already had enough strength to keep its position unchanged, which is good for the appearance quality of the wall. The amount of concrete extruded from the nozzle is not only related to the rotational speed of the extrusion screw, but also to the initial pressure of the extrusion screw. Therefore, during the printing process, it must be ensured a fixed amount of concrete in the hopper to obtain the constant pressure. This can be achieved by the camera monitoring the liquid level in the hopper and adjusting the feed rate of the peristaltic pump and the extrusion speed of the screw. Support must be added to the top of doors and windows to be printed, otherwise concrete will fall under gravity. And the support must be removed after the concrete has solidified, as shown in Fig. 9b. Figure 9c is the finished printed pavilion wall.



Fig. 9. Printing of the pavilion wall. (a) Model of the pavilion wall is divided into the stiffener and the contour; (b) The base with two tracks and the supports of the window and the door; (c) Practical printed wall.

Roof Printing

The roof can not be built without support structure. Therefore, a support frame is constructed based on the design model of the roof. In order to ensure that the printed roof fits the supporting surface perfectly, the model of the support must be obtained by reverse engineering, as shown in Fig. 10. Reverse engineering refers to the measurement of a physical model with some measurement methods. Then, according to the measured data, the physical CAD model is reconstructed by 3D geometric modeling method. The final model for slicing is the reconstructed physical model.

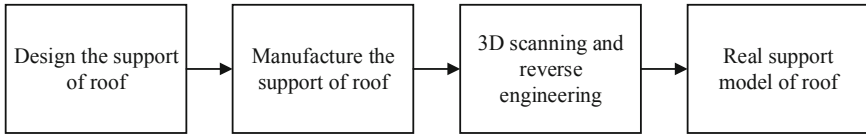


Fig. 10. Construction process of the support model of roof

The angle between the roof support and the horizontal plane is too small that the small bonding width and low bonding strength between adjacent layers, as shown in Fig. 11a. Therefore, the printing width must be increased. Without replacing the extrusion head, printing two cycles per layer, as shown in Fig. 11b, where w is the print width, h is the layer height, L is width of the overlap between the upper and lower layers. When the support is added, the position of the support model in the program must coincide with that of the actual support. Therefore, skirts must be added when slicing roof model. Which means, print one more layer on the periphery of the roof model for positioning. When the skirt edge is printed, put the support into it. A layer of steel mesh is placed on the surface of support before printing the roof to increase the strength of the structure and prevent the concrete from sliding down on the surface. The printed roof is shown in Fig. 12.

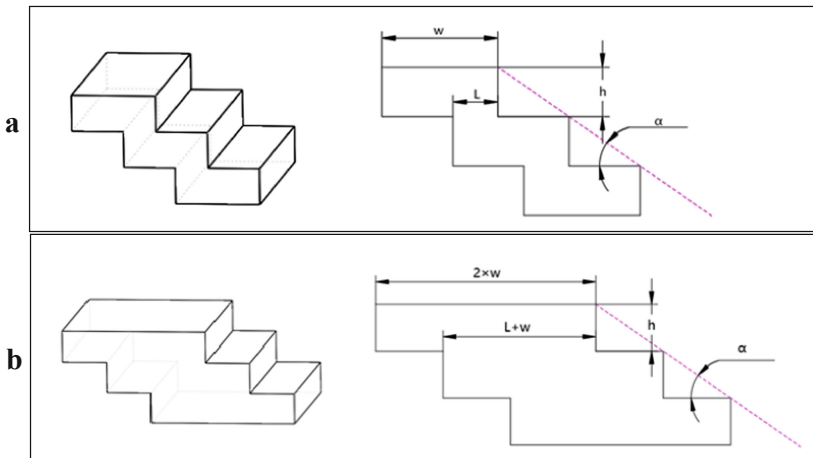


Fig. 11. Number of print cycles per layer. (a) Printing one cycle per layer; (b) Printing two cycles per layer to increase the width of bonding surface



Fig. 12. Printing of the roof. (a) The skeletal structure of the roof support; (b) Roof support with steel mesh for increasing strength; (c) Practical printed roof.

5 Discussion

Although the feasibility of the printing system and process planning has been verified by experiments, there are still some problems in system development and process planning that need to be solved including the following aspects.

The existing slicing software not only needs to process the model and generated program, but also cannot edit the generated path freely. Grasshopper is a flexible parametric design tool that allows the creation of new algorithms or the modification of existing ones in a graphical scripting environment, which can be used to develop a slicing program suitable for 3D printing of concrete.

The surface quality of the pavilion wall is not uniform, because different temperatures and humidity affect the properties of materials. Therefore, the effect of temperature and humidity on the material must be considered in the subsequent printing process. Appropriate process parameters must be matched with different temperature and humidity.

Ensuring the consistency of the width of filaments is conducive to achieving high structural strength and good appearance of the building. Therefore, the width of extruded concrete must be monitored in real time. It is necessary to develop a set of visual recognition module to automatically recognize the width of filaments. The difference between the width of the filaments and the target width is used as feedback signal, and then the speed of the motor is obtained by using the intelligent algorithm.

6 Conclusion

Concrete 3D printing as a new construction technology has developed rapidly in recent years. This work developed a concrete 3D printing system and its process planning from the point of considering the large-scale of the printer and the thixotropy of the concrete. The components of the printer were described and the screw was optimized by analyzing the fluid structure coupling of the concrete mortar in the sleeve. The problems in the process of tool path generation and parameter design were discussed. At last, the performance of the concrete 3D printing system and the rationality of the process planning were verified by a preliminary printing experiment and a pavilion printing experiment.

Acknowledgements. This work is funded by Natural Science Foundation of China (51675383), “the Fundamental Research Funds for Central Universities” and Jiangsu Renqiang Architectural Technology Co., Ltd.

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Shape Accuracy Evaluation of Geopolymer Specimens Made Using Particle-Bed 3D Printing

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Abstract. The primary benefit offered by the particle-bed 3D concrete printing process (3DCP) is the high flexibility in design for manufacture of concrete components with complex geometrical features. Accuracy evaluation has become a critical issue need to be overcome before a more widespread application of the particle-bed 3DCP technique in construction. This study reports an inexpensive image acquisition and processing technique using a flatbed scanner for shape accuracy evaluation of geopolymer specimens made using the particle-bed 3DCP process. A set of image processing algorithms is developed to extract useful shape information from the scanned images without any human intervention. Centroid distance function is used as the shape error representation under the Polar coordinate system for the shape error measurement. A color-labeled map in conjunction with the root mean square error are used for assessment of the shape accuracy. The results show that the developed method can satisfactorily be used for shape accuracy measurement of the particle-bed 3D printed specimen.

Keywords: Digital construction · Particle-bed 3D printing · Geopolymer · Shape accuracy · Image analysis

1 Introduction

The primary benefit offered by application of 3D printing in construction is high flexibility in design. Complex geometries that are difficult or impossible to produce using conventional construction processes can be made using 3D construction printing techniques [1]. Difficulties in meeting stringent requirements regarding dimensional and shape accuracies have become a critical issue that needs to be overcome before having widespread application of 3D printing techniques in construction industry [2, 3].

Recently, extensive research work in the 3D construction printing field has been conducted to address issues such as developing suitable equipment, developing and characterizing different printable materials and designing feasible reinforcement methods. However, studies related to the dimensional and shape accuracies of 3D

printed components received less attention. Lim et al. [4] used a laser scanning technique to evaluate the manufacturing tolerances of extrusion-based 3D printed components against the original computer-aided design (CAD) model.

The fundamental principle for accuracy assessment is to evaluate the deviation degree between the actual part and the nominal part, for instance, the CAD model. Several measuring techniques have been developed and adapted to meet the metrological requirements in particle-bed 3D printing [5–9]. For the measurement of simply manufactured parts, the digital caliper is the most commonly used tool for the assessment of linear accuracy. However, the measurement uncertainty is highly dependent on the skills of operators. For manufactured parts with more complex geometry, coordinate measuring machine (CMMs) and X-ray computed tomography (CT) have become an accepted measuring tool for accuracy assessment in the field of additive manufacturing. However, analysis of a part can be time-consuming for an operator from one sample to the next. Meanwhile, both of these measuring techniques usually require a massive capital investment.

A potential cost-effective option for use in construction industry would be a flatbed scanner. Flatbed scanners have been used by construction researchers to measure the amount and size distribution of porosity in hardened concrete and mortars [8], characterization of frost damage of concrete [10] and analysis of air voids in concrete [11]. These studies generally indicated that a flatbed scanner could provide a low-cost and convenient alternative to digital image acquisition, while having high resolution, high optical density, and low image distortion features. Marchment et al. [12] used a flatbed scanner and a unique method of image processing to quantitatively determine the ‘effective bond’ area between extrusion-based printed layers.

This research evaluates the capability and practicality of using a flatbed scanner to assess the shape accuracy of particle-bed printed components. The outcome of this research can enable a reasonably fast quality control method in digital construction.

2 Materials and Methods

2.1 Materials

A printable geopolymer-based powder (denoted as GP) developed by the authors was used for printing the test component. The GP powder was a mixture of slag, anhydrous sodium metasilicate powder and a high purity fine silica sand. An aqueous solvent (Zb[®] 63, Z-Corp, USA) was used as the binder solution. Zb[®] 63 was an aqueous commercial clear solution with the viscosity similar to pure water. The composition of Zb[®] 63 was mainly water with 2-Pyrrolidone. Further details regarding the preparation of the printable geopolymer powder and the liquid binder can be found in the authors’ previous study [13].

2.2 Design of Test Component

A test component measuring 40.4 mm (L) × 40.4 mm (W) × 4 mm (H) was designed by using a CAD software (SolidWorks[®] 2018, SolidWorks Corp., USA) for the

assessment of shape accuracy in x - y plane. This test component consisted of three shapes of holes (namely circle, triangle and square) with varied dimensions ranging from 0.5 mm to 5 mm. The 3D model and 2D drawing of the test component are shown in Fig. 1. The coordinate system of the test component is in accordance with the axes of the particle-bed 3D printer. The x -axis is the direction of binder jetting, the y -axis is the direction of the powder layer spreading and the z -axis is the direction of layer stacking.

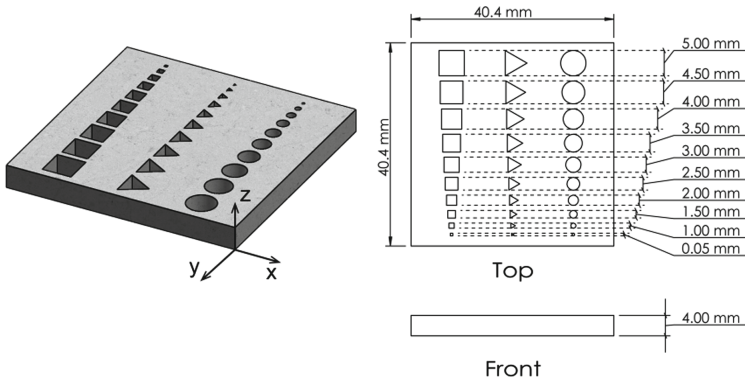


Fig. 1. CAD-designed test component for x - y plane shape accuracy assessment.

2.3 3D Printing Process

The test component was manufactured by using a commercial particle-bed 3D printer (Zprinter[®] 150, Z-Corp, USA) with an HP11 print head (C4810A). The Zprinter[®] 150 has a specified resolution of 300×450 dpi and a 236 (L) $\times$ 185 (W) $\times$ 132 (H) mm³ build volume. The layer thickness of 0.1016 mm with 75% binder saturation level were selected for the 3D printing process. Binder saturation level is defined as the ratio between the volume of deposited binder liquid (V_{binder}) and the volume of pores in the powder bed (V_{pores}). This printing parameter combination was chosen to achieve the highest accuracy result [14, 15]. The printed test component was dried within the powder bed at room temperature for 2 h and the unbound powder was then removed via compressed air. No further post-processing procedure was applied.

2.4 Image Acquisition of Test Component

The images of the printed test component were captured using a commercially available flatbed desktop scanner (Hewlett-Packard[®] Scanjet G3010), which has a maximum optical resolution of 4800×9600 dpi.

The images were scanned at a resolution of 1200 dpi by using a software bundled with the scanner. With such scanning resolution, the minimum point size that can be detected is 21.2 μm . It should be pointed out that the scanning resolution is not limited to 1200 dpi, as increasing scanning resolution can heavily increase the analyzing time

and beyond 1200 dpi the measurement of the 1 mm cannot be improved [16]. In this study, the scanning time of the printed test component was 90 s.

All automatic correction and enhancement functions were disabled to ensure the raw images were not manipulated. The images were saved with a 24-bit Tagged Image File Format (tiff).

2.5 Image Processing Algorithms

The images acquired from the flatbed scanner were then processed to obtain the shape information of the holes (region of interest, ROI) on the printed test component. A combination of image processing algorithms was developed using MATLAB® Image Processing Toolbox to extract boundaries of the holes. The main goal of this combination of algorithms is to characterize the shape of the holes by extracting useful shape information from scanned images without any human intervention.

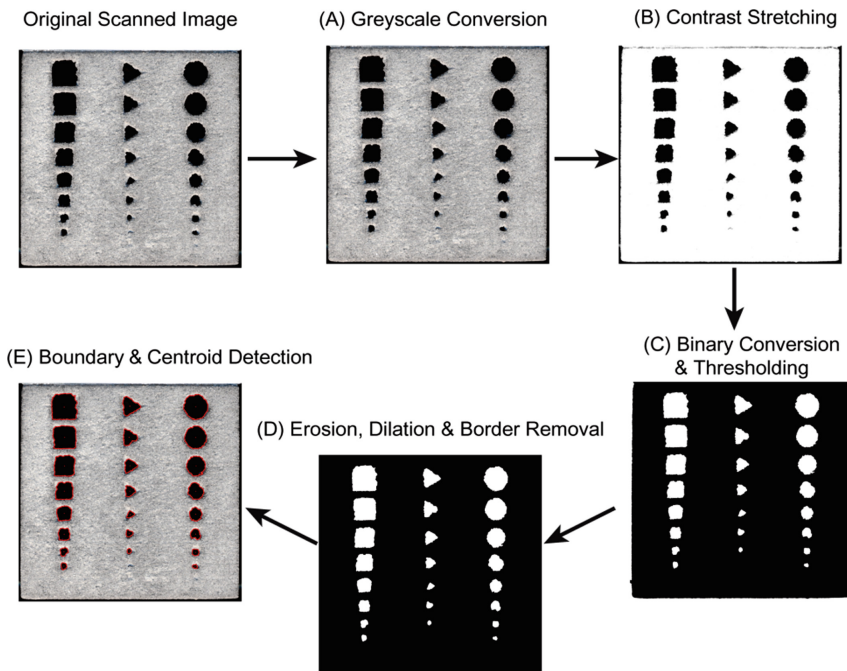


Fig. 2. Key steps of the image processing algorithms.

As is illustrated in Fig. 2, the developed algorithms contain several steps, including (A) Grayscale Conversion, (B) Contrast Stretching, (C) Binary Image Conversion & Thresholding, (D) Erosion, Dilation, and Border Removal and (E) Shape Boundary and

Centroid detection. These key steps were applied to the raw images in sequence to extract holes' boundaries and centroids information.

2.6 Representation of Shape Errors in the X-Y Plane

In this study, a one-dimensional function named 'Centroid Distance Function' was used to capture the perceptual feature of the shape [17, 18]. The Centroid Distance Function is derived from centroid and shape boundary coordinates, and can be expressed by the distance of the boundary points from the centroid of shape either in a Cartesian coordinate system using coordinates (x,y) or in a Polar coordinate system using (ρ, θ). The Polar coordinate system is preferred as it greatly facilitates the shape boundary representation. In the Polar coordinate system, the radius ρ at an angle θ is a function of θ and ρ₀(θ) and is expressed as ρ(θ, ρ₀(θ)). Thus, the shape error can be defined as the difference between the actual radius and nominal radius at an angle θ, as shown in Fig. 3. The shape error Δρ can be expressed as:

$$\Delta\rho = \rho_{\text{actual}} - \rho_{\text{nominal}} \quad (1)$$

where ρ_{actual} and ρ_{nominal} are the actual and nominal radius at an angle θ, respectively.

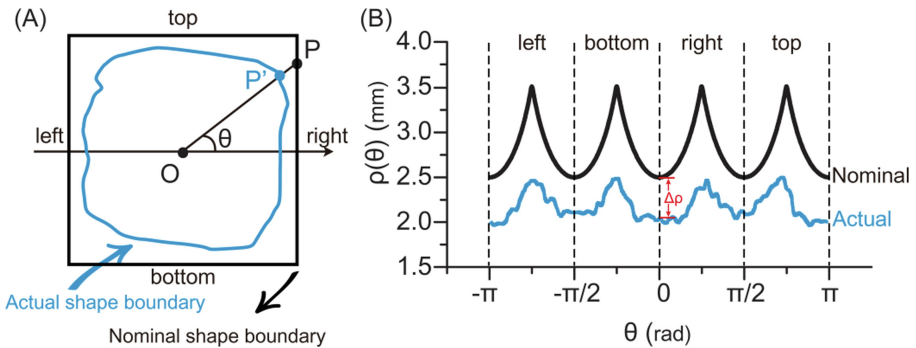


Fig. 3. (A) Schematic of shape error in the Polar coordinate system, (B) Example of Centroid Distance Function of nominal and actual shape boundary.

2.7 Measurement of the Shape Error in the X-Y Plane

After detection of the shape boundary and centroid, the coordinates of actual shape boundary pixels were given in a list of (x_i, y_i) pairs in Cartesian coordinate system. The centroid (C_{x_i}, C_{y_i}) of each ROI as computed according to Eq. (2).

$$\begin{aligned} C_x &= \frac{1}{6A} \sum_{i=0}^{N-1} (x_i + x_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \\ C_y &= \frac{1}{6A} \sum_{i=0}^{N-1} (y_i + y_{i+1})(x_i y_{i+1} - x_{i+1} y_i) \end{aligned} \quad (2)$$

where N is the number of pixels on the shape boundary, and A is the contour's area that can be calculated using Eq. (3):

$$A = \frac{1}{2} \left| \sum_{i=0}^{N-1} (x_i y_{i+1} - x_{i+1} y_i) \right| \quad (3)$$

The detected ROIs were categorized into three groups (Square (l), Triangle (m) and Circle (n)) according to the coordinates of their centroids, where l , m , n are the numbers of ROIs in the corresponding groups and $l + m + n = N_{\text{ROI}}$. (where N_{ROI} is the number of detected ROIs).

In each group of ROIs, for every dimension (k) of the holes, the coordinates of nominal shape boundary pixels were generated using the *nominal shape function* as listed in Table 1.

For simplicity, the centroid of the generated nominal shape boundary is the same as the actual shape boundary. The nominal shape function was created to output the coordinates of the hole's nominal boundary pixels based on the centroid (Cx_i , Cy_i) of corresponding actual shape boundary.

The actual and nominal shape boundary were then transformed into the Polar coordinate system. For each shape with different dimensions (k), the shape error $\Delta\rho$ at each θ ($\theta \in [-\pi, \pi]$) was calculated according to Eq. (1). Accordingly, the sum of the shape errors was used to assess the shape accuracy for a given dimension. Moreover, the sum of the shape errors for all dimensions was considered as an evaluation for shape accuracy assessment.

Table 1. The nominal shape functions of three shapes.

Shapes	Nominal shape functions, $\rho(\theta)$	
Square	$\rho(\theta) = \begin{cases} \sqrt[3]{\frac{k}{6 \sin(\frac{5}{6}\pi - \theta)}} & \theta \in [0, \frac{2}{3}\pi) \\ \sqrt[3]{\frac{k}{6 \sin(\frac{1}{6}\pi - \theta)}} & \theta \in [-\frac{2}{3}\pi, 0) \\ \sqrt[3]{\frac{k}{6 \cos(\pi - \theta)}} & \theta \in [-\pi, -\frac{2}{3}\pi) \cup (\frac{2}{3}\pi, \pi] \end{cases}$	$\theta \in [-\pi, \pi];$ k is the dimension of the holes ranging from 0.5 mm to 5 mm
Triangle (Equilateral)	$\rho(\theta) = \begin{cases} \left \frac{k}{2 \sin(\theta)} \right & \theta \in [-\frac{3}{4}\pi, -\frac{1}{4}\pi) \cup [\frac{1}{4}\pi, \frac{3}{4}\pi) \\ \left \frac{k}{2 \cos(\theta)} \right & \theta \in [-\pi, -\frac{3}{4}\pi) \cup (\frac{3}{4}\pi, \pi] \end{cases}$	
Circle	$\rho(\theta) = k$	

2.8 Assessment of Shape Accuracy

When interpreting the results acquired from the shape error measurement, a color-labeled map in conjunction with the root mean square error (RMSE) was used for the assessment of shape accuracy in the x-y plane.

A color-labeled map was created by using shape errors. This map graphically shows the distribution of the shape errors.

3 Results and Discussion

The distribution of shape errors of the test component is shown in Fig. 4. As can be seen, the shape errors were in negative values, indicating that all shapes were undersized. This is true regardless of dimensions of the shapes. The undersized small holes in the particle-bed 3D printing process can be explained by the bleeding mechanism, as consequence of the binder spreading outside the part contour [19].

Regardless of the dimension of the shapes, the maximum deviations in the rectangular shape and triangle shape were observed in the angle regions. With regard to the circular shape, the distribution of deviations was much more homogenous as compared to the other two shapes.

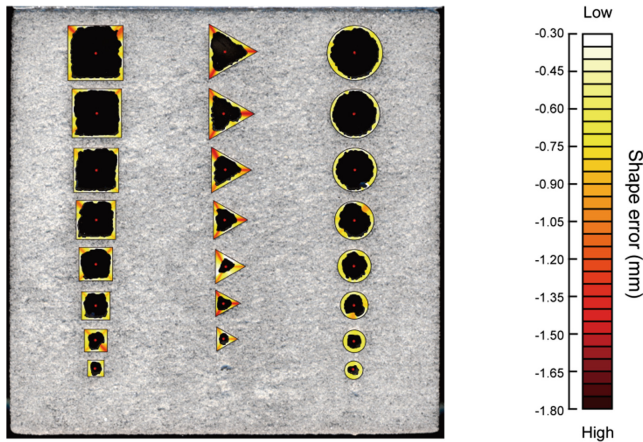


Fig. 4. Shape error map of the test component.

4 Conclusion

The shape accuracy in the x-y plane for components made using particle-bed 3D printed has been assessed in this study. A flatbed scanner was used as a high-quality image acquisition apparatus. A combination of image processing algorithms was developed to extract the boundary of region of interests. The centroid distance function was used as the measurement of shape errors. The following conclusions are drawn:

- (1) The boundary information of different holes in the test components can be extracted satisfactorily after the application of the developed image processing algorithms.
- (2) The Centroid Distance Function in the Polar coordinate system is an efficient tool for the interpretation of the shape error.
- (3) The maximum deviations in the rectangular shape and triangle shape were observed in the angle regions. With regard to the circular shape, the distribution of deviations was much more homogeneous as compared to the other two shapes.

The proposed shape accuracy evaluation method based on 2D image can enable a reasonably fast quality control process in digital construction. However, as a preliminary study, the limitation of the proposed method is that only plane and small sized elements can be evaluated due to the size limitation of flatbed scanner. Further research is needed in order to ensure the proposed method can be adapted to large-scale construction application.

Acknowledgments. The authors gratefully acknowledge the support by the Australian Research Council Discovery Grant DP170103521, Linkage Infrastructure Grant LE170100168, and Discovery Early Career Researcher Award DE180101587. Authors also acknowledge Building Products Supplies Pty Ltd., Australia, Redox Pty Ltd., Australia and TGS Industrial Sands Pty. Ltd., Australia for supplying the materials used in this study.

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Sustainability, LCA & economical analyses



Environmental Impacts of 6-Axes Robotic Arm for 3D Concrete Printing

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Abstract. This paper presents an environmental assessment of a 6-Axis robotic Arm for extrusion-based 3D Concrete Printing technology using Life Cycle Assessment method. In addition, the other components of a printing cell are assembled within a life cycle model and the relative contribution of the cell to the printing process is evaluated. The results show that, per one hour of printing, an environmental impact coming from the production phase of robotic printing cell would represent 2,2 kg CO₂ Eq for the category of Climate Change. Hourly contributions are also calculated for the rest of environmental indicators.

Keywords: LCA · 3DCP · Additive manufacturing · Computational design

1 Introduction

Concrete is the most used construction material in the world and the second most consumable resource after water [1]. From historical perspective, the increase of concrete consumption in a given place is directly related to industrial development of a territory and to its urban expansion. Thus, only in 2011–2013 China produced a close amount of concrete that United States did during XX century [2], and those statistics would only tend to increase considering the ongoing urban development in the world. Therefore, as it was pointed out in [3], it is not exactly the environmental cost of concrete itself, but its gigantic amount consumed yearly (about 10 km³/year) that provokes a critical environmental urgency in the sector.

The high environmental impact of concrete is mainly related to the CO₂ emitted during the chemical reactions of cement preparation as well as to the energy-intensive character of those processes. Otherwise, the rest of raw constituents needed for the concrete composition are usually local, e.g. sand and gravel, and today, within environmental sciences, considered as unlimited resource with relatively low embodied impact. Furthermore, at the scale of a building system or infrastructure element, e.g. beams, slabs or columns, it was demonstrated in [4] that conventional construction processes by casting contribute little to the environmental impact of final elements. In general, the on-site construction represents only around 2% of buildings total impact [5, 6].

Summing up, at the scale of material, the environmental improvement lies mainly in cement substitution with alternative binders [3]. At the scale of building systems or infrastructure element, even greater optimization potential features in widely debated capacity of the more rational material deposition offered by digital additive manufacturing, largely known as 3D Concrete Printing.

At this point, when the concrete gets to be deposited with 6 axis industrial robot, the main question from an environmental standpoint is whether this fabrication process remains insignificant within the overall life cycle (impact transfer) and, furthermore, whether it brings some new pollutant to the system (pollution shift) in some previously neglectable environmental categories?

The present study conducts an environmental evaluation of 3D Concrete Printing technology with a specific focus on the contribution made by robotic printing system to the overall impact. Thus, a detailed life-cycle model of a printing cell based on 6-axis robot technology is assembled and its outlay to the printing process is discussed.

2 Background

Previously, only few researches have been studied an environmental impact of digital fabrication processes in construction. Agusti-Huan et Habert performed a seminal work in the field [16], comparing digitally fabricated elements with ones fabricated conventionally pointing out a strong potential of the first in terms of material reduction. A specific study was effectuated for Mesh Mould wall system [9], similarly interrogating its environmental viability over a conventionally fabricated concrete wall. The results demonstrated a fair advantage of digital fabrication processes when complex, and precisely curved geometries are concerned. However, the mobile robotic technology assessed remains largely experimental and hardly represents today's industrial set-ups for robotic printing cells.

Some exploratory studies have also been guided on the above-mentioned problematic of a possible trade-off between material savings and additional burden related to digital fabrication processes, pointing out a fair importance of the last [7, 8].

The present paper is specifically focused on the extrusion-based additive manufacturing with cement-based materials, aka 3D Concrete Printing (3DCP) and particularly studies the contribution of a 6-Axis robotic arm to the printing process in terms of environmental impact. The methodology and the analysis model are presented in the next section.

3 Methodology

The environmental evaluation of the present study uses Life Cycle Assessment method. Framed by International Standards 14040 et 14044 [10, 11], in brief, the method consists in tracking all the energy and resources needed for system's functioning from production phase to the end-of-life. These flows are then translated into an environmental impact of the system within different impact categories, e.g. climate change, toxicity, resources depletion, eutrophication etc. The method thus allows to quantify

the environmental quality of the system and to monitor potential impact transfers between the life cycle phases. Its multicriteria aspect is supposed to prevent a pollution shift from one environment to another.

The system boundaries of the present study are set from cradle to gate (A1–A3 according to EN 15804), as the problematic addresses mainly the fabrication phase. Within the hypothesis of the recycling of all robotic hardware by the manufacturer, no end-of-life treatment is considered [12]. The entire inventory is modeled using EcoInvent 3.2 cut-off database within the OpenLCA software. All processes are taken with their market version, i.e. average transport for its components, offering a universal model independent from geographical location. Recipe midpoint (H) method of impact calculation was taken, following the ILCD Handbook recommendations [13] (Fig. 1).

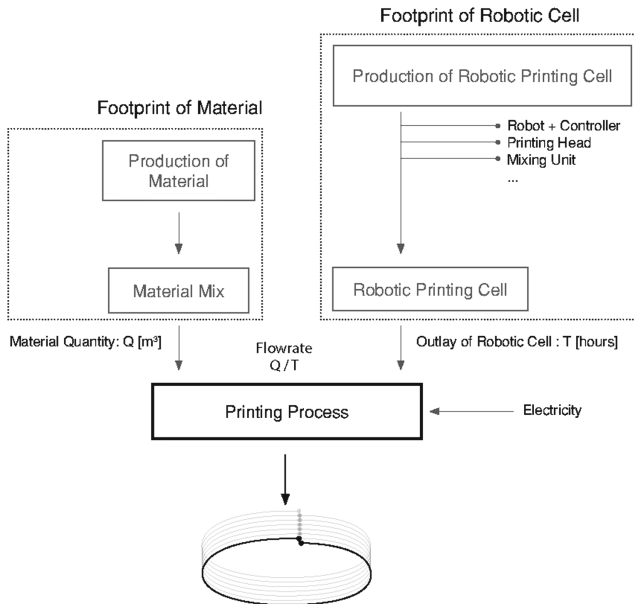


Fig. 1. Life-cycle model diagram of printing process

Two main flows enter the process of reference: the quantity of material (m^3) and the working time (h) of robotic 3D Printing Cell. The compromise between these two flows is the fundamental question of this study. The sum of their respective footprints would thus represent a global system's impact. Therefore, if the environmental footprint of cement-based materials has been extensively studied previously [3], the footprint of Robotic Printing Cell is assessed and explained in the next section.

4 Footprint of 6-Axis Robotic Cell

The data collection of the inventory is done in collaboration with XtreeE [15] company and largely based on its technical set-up. Figure 2 depicts the lay-out of the printing cell. It is composed of a 6-axis industrial robot ABB IRB 8700 carrying the printing head, developed in-house (4), supplied from the mortar-mixing unit (3). A computer workstation commands the system (2). Again, all inventory is modeled with world's average data, with no geographic or industrial specificities. Therefore, the final life-cycle model is expected to represent a generic set-up for any 3D Concrete Printing cell based on 6-axis robot.

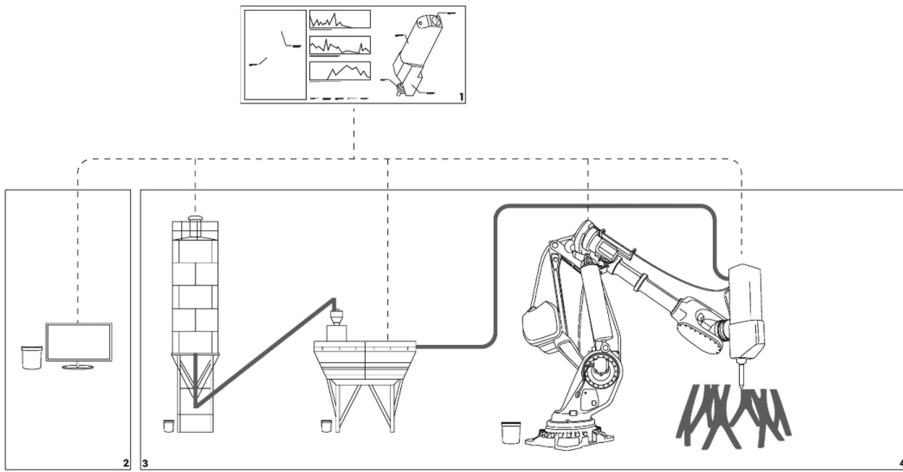


Fig. 2. XtreeE printing system: 1. Digital model; 2. Management platform; 3. Concrete mixing unit; 4. 6-Axis robot & printing head. Image: Courtesy of XtreeE

The absolute values of Life Cycle Assessment of robotic printing cell are presented in the Table 1. The lifespan of the cell is set in reference to the one of the robotic arm. The maintenance and replacement rate of components is set accordingly. In literature, the robot's life service is usually set to 8–10 years [16, 15]. As reported in manufacturer documentation *“the robot's life-cycle seldom exceeds 20 years”* [17]. In reality, the life expectancy of a robot would depend of exhaustion of its servo-motors, which is a function of bidding speed and torque as well as of duty cycles. In analogous industries, this function is usually simplified to a simple coefficient, e.g. a number of traveled kilometers for cars or number of on-off cycles for electronics. In addition, Concrete 3D Printing technology requires hardly an intermediate running power of robot: the toolpaths beyond 2.5 axes only start to develop [18], but under any circumstances, the material-related constrains would doubly let the printing process go much faster. Thus, basing our analysis on data from manufacturer documentation, conversations with experts [14, 19] and existing literature, a lifespan of 30'000 h is considered here.

Table 1. Environmental impact of printing cell based on 6-axis robotic arm

Impact category	Units	Total impact per lifespan
Agricultural land occupation	m²a	8,2e+03
Climate change	kg CO₂-Eq	6,6e+04
Fossil depletion	kg Oil-Eq	1,8e+04
Freshwater ecotoxicity	kg 1,4-DCB-Eq	6,5e+03
Freshwater eutrophication	kg P-Eq	1,2e+02
Human toxicity	kg 1,4-DCB-Eq	2,0e+05
Ionizing radiation	kg U₂₃₅-Eq	4,7e+03
Marine ecotoxicity	kg 1,4-DCB-Eq	6,1e+03
Marine eutrophication	kg N-Eq	9,5e+01
Metal depletion	kg Fe-Eq	6,1e+04
Natural land transformation	m²	1,0e+01
Ozone depletion	kg CFC-11-Eq	4,1e-03
Particulate matter formation	kg PM₁₀-Eq	2,8e+02
Photochemical oxidant formation	kg NMVOC	2,8e+02
Terrestrial acidification	kg SO₂-Eq	5,9e+02
Terrestrial ecotoxicity	kg 1,4-DCB-Eq	1,0e+01
Urban land occupation	m²a	1,3e+03
Water depletion	m³	2,7e+02

4.1 Outlay of Robotic Cell to the Printing Process

The outlay of technical equipment to the fabrication process has been little discussed in existing academic works on the topic. In the present paper, it is one of the major points as it defines the relative contribution of robotic cell to the printing process. Commonly, within the LCA discipline, the outlay/amortization of technical equipment is calculated as the percentage of their life-cycle impact dedicated to the production of Functional Unit. Thus, in the present study, the outlay of robotic cell is represented with the quotient of 1 h of printing divided by the whole lifespan of the cell. Thus, per one hour of printing, the system will collect 0,003% of the impact related to the production and fabrication of the robotic cell components. As follows, the hourly contribution of robotic printing cell to the printing process is shown in Table 2 for all environmental categories of impact.

Table 2. Hourly impact of robotic printing cell

Impact category	Units	Total impact per lifespan
Agricultural land occupation	m²a/hour	0,3
Climate change	kg CO₂-Eq/hour	2,2
Fossil depletion	kg Oil-Eq/hour	0,6
Freshwater ecotoxicity	kg 1,4-DCB-Eq/hour	0,2
Freshwater eutrophication	kg P-Eq/hour	4e-03
Human toxicity	kg 1,4-DCB-Eq/hour	6,7
Ionizing radiation	kg U₂₃₅-Eq/hour	0,15
Marine ecotoxicity	kg 1,4-DCB-Eq/hour	0,2
Marine eutrophication	kg N-Eq/hour	3,2e-03
Metal depletion	kg Fe-Eq/hour	2
Natural land transformation	m²/hour	3,4e-04
Ozone depletion	kg CFC-11-Eq/hour	1,4e-07
Particulate matter formation	kg PM₁₀-Eq/hour	0,01
Photochemical oxidant formation	kg NMVOC/hour	0,01
Terrestrial acidification	kg SO₂-Eq/hour	0,02
Terrestrial ecotoxicity	kg 1,4-DCB-Eq/hour	3,5e-04
Urban land occupation	m²a/hour	0,04
Water depletion	m³/hour	0,01

5 Conclusion

The ongoing development of 3D Concrete Printing technology is usually accompanied by an argument of its sustainable potential, based on a largely discussed capacity of more precious and rational material deposition offered by additive manufacturing.

The present study performed a life cycle assessment of a printing cell based on a 6-axis robotic arm, in order to evaluate its contribution to the overall environmental impact of the printing process. It shows that, only for the Climate Change category, the impact coming from production of robotic printing cell represents 2,2 kg CO₂ Eq per hour of printing, which equals to a carbon footprint of an average passenger sedan car driven over 20 km [20]. Otherwise, regarding the rest of indicators a supplementary normalization step is necessary to understand the pollution shift happened within. At the present analysis, no burden related to the operational energy of printing process was studied. The much-required exact quantification of the last would thus allow to meet the respective impacts of robotic printing cell and material in order to evaluate the overall environmental impact of a printed element.

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Preliminary Productivity Analysis of Conventional, Precast and 3D Printing Production Techniques for Concrete Columns with Simple Geometry

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Abstract. Significant advancement has been made in the field of additive manufacturing as applied to the construction industry. However, little attention has been paid to the implications of additive manufacturing, in particular 3D concrete printing (3Dcp), on the productivity of construction projects. The purpose of this study is to conduct a preliminary analysis of the productivity, measured in terms of cost and time per amount of material, for the construction of simple geometry concrete columns using conventional, precast, and 3Dcp techniques. The complexity of the geometry that can be achieved using 3Dcp was not factored in the comparison. Discrete-event simulations with data from the Concrete Choreography project were run. These results were compared with the productivity level achieved in the construction of a reinforced concrete column using conventional and precast construction methods. As expected, it was found that for the construction of simple geometry columns, 3Dcp is still not as productive as the other methods. These results should not be misunderstood as a lack of competitiveness of 3Dcp versus traditional methods. On the contrary, these results highlight the many benefits and capabilities of 3Dcp, which surpass the cost and time components. Some of them include topological optimization, geometric freedom, as well as increased transparency during the planning, design, and construction processes, which bring tremendous value to the 3Dcp elements. Quantifying these benefits is not trivial and is beyond the scope of this study; however, ongoing research is being conducted to address that.

Keywords: Additive manufacturing · Construction automation · Digital fabrication · Labor productivity · Time and cost analysis

1 Introduction

1.1 3D Printing: Is It as Good as It Sounds?

3D concrete printing (3Dcp) is rapidly gaining attention in both academia and in architecture, engineering, and construction (AEC) industries. For example, the number

of articles published on the topic of 3Dcp on the Web of Science has risen from 15 in the time period until 2015 to 150 in 2019 alone. This interest in 3Dcp often cites the technology's potential to decrease construction cost and time [1]. Following a similar trend, public media is reporting that many companies like New Story, a housing nonprofit organization, and Icon, a technology company, have “built [several 3D printed homes] in 24 h” [2]. This further propels the image of 3Dcp as a revolutionary construction method that improves the productivity of any construction project. Today, universities and companies around the world have successfully completed the construction of several bridges [3, 4], houses [5, 6], and even a 500-m long revetment wall [7] and military barracks [8]. Furthermore, the appeal for 3Dcp has resonated on a governmental scale, and in 2016, the United Arab Emirates (UAE) announced the Dubai 3D printing strategy, which sets a goal that every new building is at least 25% 3D printed by 2030 [9]. Since then, the UAE has promoted the construction of the world's first 3D printed office space [10], a drone research lab [11], and residential villas [12]; the UAE has also recently printed the world's largest two-story building [13]. These projects hope to cement “UAE and Dubai [as] a leading hub of 3D printing technologies by the year 2030” [9] and this ambitious ecosystem has been populated by several 3Dcp companies like Besix3D [14], CyBe [15], Concreative [16], 3DVinci [17], and ACCIONA [18], to name a few.

Nevertheless, some of the reported information is often misleading [19, 20]. While the actual printing time of individual concrete members can take several hours, the reported figures exclude the additional time required to complete the project. Extra time is needed to install other building elements such as the roof, floors, windows, MEP¹, and other components pertinent to any building, as well as the minimum curing time required². For example, the Office of the Future in Dubai was printed in 17 days, yet the installation of all other building components required three additional months [10]. While this is still a noteworthy achievement, the initial presentation implies a distorted representation of the building process, which can lead to false expectations. On top of that, in some cases (for example, as indicated by New Story) the printing time reported only accounts for the duration required for the robot to lay down the layers and does not include the time required for the layers to cure to the extent that they can support the subsequent layers [21]. Nor do these figures account for the curing of the final concrete element. The equivalent of this in conventional construction would be specifying only the time required for installing the formwork. Reporting the impact of 3Dcp in such a way paints an unrealistic image of the potential of the technology, creates false expectations for clients, and negatively impacts the 3Dcp industry. Such false-advertisement had been taken advantage of by some companies. For example, Cazza promised to 3D print an 80-story, 750-m skyscraper in Dubai by 2020 [22], yet was not straightforward about the state of its technology; ultimately, the project was abandoned, and the company was dissolved [23]. It seems that 3Dcp is still experiencing “the peak of inflated expectations” as per the Gartner hype cycle [24]. Nevertheless, it is clear that

¹ Mechanical, electrical, and plumbing.

² E.g., a minimum curing period of seven days for ambient temperatures above 4.5 °C is typically required for reinforced concrete elements.

3Dcp offers a set of other benefits like freedom of shapes, topological optimization, and others beyond the potential reduction of construction costs and duration (see Sect. 1.4). It is in part the goal of this paper to address this problem of overestimating the effect of 3Dcp by providing an accurate comparison of 3Dcp versus conventional construction methods in terms of their impact on costs and time required.

1.2 Productivity in the Construction Industry

If, by implementing 3Dcp and other modes of digital fabrication, the construction industry could match the average productivity of the total economy, it could experience a boost in value of \$2.11 trillion (in 2019 dollars). This growth could add enough value to the industry to meet half of the global infrastructure demands [25]. After all, the current productivity in the AEC industry is mostly estimated to be subpar, but details are unclear. Some sources report that it has declined [26], while others claim that from 2006 to 2016, productivity grew by 5.3% in industrial construction [27]. Often the reason for such disputes is the complexity in using appropriate economic deflators that are meant to convert revenues into more indicative long-term growth measurements. Nevertheless, the trend of AEC lagging behind other industries remains consistent across literature.

One might wonder, is the AEC industry less productive in nature than other industries? Even if the answer is yes, the room for improvement is clear as the construction industry is the second least digitized industry in the US, and it ranks last in Europe [28]. This raises opportunities of unrealized potential for improved productivity as increased permeation rates of digital technology [29] and robots [30] are set to improve the productivity of the industry. New technologies like 3Dcp can enhance that. As an example, past implementation of Building Information Modeling techniques and digital design have already decreased construction times and costs [31].

1.3 Main Objective

The main objective of this study is to compare three different construction techniques (conventional, precast, and 3Dcp) in terms of their productivity during the construction phases of a column with a simple geometry. Furthermore, we wish to draw attention to 3Dcp (or additive manufacturing in general) as a way of improving 1) construction planning, 2) control and tendering practices, 3) long-term value of the concrete element, 4) overall construction processes, and 5) other stages in the life-cycle of construction projects.

1.4 Benefits of 3Dcp

While costs and durations are significant factors in determining an applicable construction method, 3Dcp offers a myriad of other advantages besides the potential productivity benefits. It is important to note these factors to better understand the total value, including the long-term value, per cost of a concrete element instead of resorting to only the manufacturing costs as the determining factor in evaluating 3Dcp. This is important as, ultimately, the value of the produced elements is what justifies the

incurred costs. We report several of the benefits of 3Dcp; for a more elaborate overview of the state of 3Dcp, including the existing technology, benefits, and challenges, the reader is referred to other studies [32].

Geometric Freedom. 3Dcp can create shapes of great geometric freedom. This could prove useful in designing more livable and architecturally-pleasing cityscapes as good public spaces are important for the overall health of communities [33]. They are currently dominated by rectilinear forms; complex shapes are difficult, expensive, or unfeasible to create with conventional methods (e.g., traditional formwork, which is either prefabricated or manufactured on-site and can constitute the majority of the cost of the concrete elements). Indeed, 3Dcp is often explored as an option for stay-in-place formwork. Realizing this use, the formwork company PERI has invested in COBOD [34], a Danish 3D printing company that built Europe's first 3D printed house known as "The BOD" house [5]. In fact, the effect of increased geometric complexity on construction time and cost has been studied for other digital fabrication methods like the mesh mould wall developed at ETH Zurich [35]. The authors discovered that using the in-situ fabricator becomes more productive than using a conventional method when the considered geometry becomes more complex. It can be deduced that the same applies to 3Dcp.

Topological Optimization. Because of the ability to create shapes of geometric freedom, 3Dcp allows for topologically optimized designs that reduce the usage of materials by applying material only in locations where it is required for structural, aesthetic, or other purposeful reasons. This enables the creation of more sustainable concrete elements, similar to how Smart Dynamic Casting, a different digital fabrication method that utilizes topological optimizations, has showcased it [36]. Even more, prestressing used together with topologically optimized material can greatly reduce the amount of material in a printed element [37]. This is important because concrete is the second most-consumed material in the world [38], and twice as much concrete is used in construction as all other building materials combined [39]. Put this in perspective, so much concrete will be used that the world is estimated to build a new New York City every month for the next 40 years [40]. As cement is responsible for approximately 8% of global [41] greenhouse gas emissions, optimizing its usage can mitigate its negative impact on the climate. Nevertheless, 3Dcp requires paste-rich materials with a small maximum aggregate size to warranty workability, and thus a higher cement content per unit of material, making this less sustainable. Indeed, what is often called printed "concrete" is actually a mortar, with maximum aggregate sizes often 3 mm or less [42]. Therefore, material optimization must be vast to obtain environmental benefits [43], so future research on more sustainable materials is crucial.

Additional Functionality. 3Dcp can improve the functionality of the final product [44] by, for example, improving heat and sound insulation [1] of the printed element. This reduces future costs of installing such insulations. Also, 3Dcp allows for the integration of MEP systems, which, in return, can maximize the usable space. Such applications could be particularly useful in sky-rises, as in the case of the 3for2 project, in which the integration of MEP systems into structural elements saved as much as one-third of the building height [45].

Unique Applications. 3Dcp has also been used for more socially-responsible projects like the 3D printed homes by Icon and New Story, which are specifically for people from low-income backgrounds. They have printed two buildings in Mexico, which will be sold for less than \$10,000 over a payment period of several years with no interest to families living on \$3 per day [46]. Such work shows that 3D printing could be used for people from low-income backgrounds, as emergency relief and in difficult-to-access locations. The latter reason is why some research groups are exploring the possibilities of using 3Dcp on Mars [47], and NASA is organizing competitions to develop 3D printed habitats on our neighboring planet [48].

Increased Transparency in Project Planning. Further implementation of digital fabrication methods like 3Dcp can increase the transparency of how much time, materials, costs, and labor are required for construction projects. Such added clarity could help clients willing to invest in projects using 3Dcp to know if the estimated costs and duration of a project are accurate. This is particularly relevant as forecasters tend to underestimate such parameters during the tendering process in order to acquire the job [49], resulting in frequent delays and budget overruns. In addition, as illustrated in Fig. 1, the use of digital technologies can shift the frequency of changes performed in a construction project towards the design and conceptualizing phases [50]. As the cost of changes in these stages is relatively lower, further implementation of digital technologies, including 3Dcp, can help to reduce costs.

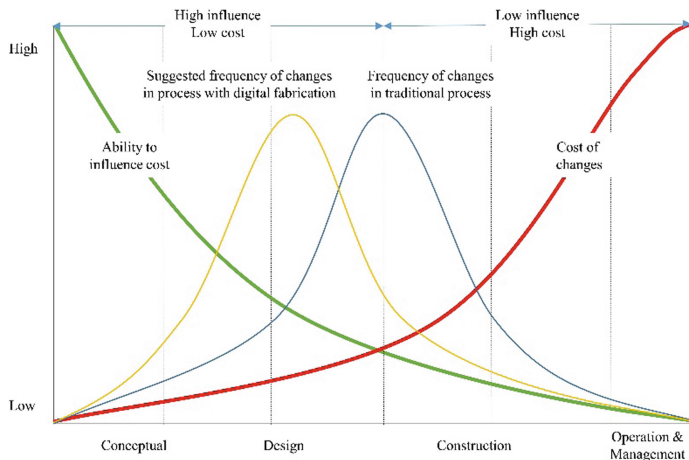


Fig. 1. Cost of changes with respect to the construction phase (adapted from [51])

2 Methodology

This paper discusses three different approaches for building a concrete column to compare the productivity levels achieved with different construction methods, namely conventional, precast, and 3Dcp (refer to Sect. 3 for more information). Although

definitions for construction productivity differ [52, 53], it is generally measured as the output per unit of input. In this study, the productivity has been measured as the cost and time per amount of material according to Eq. (1).

$$P = \frac{I}{O} \quad (1)$$

Where P is the productivity, I is, in the case of cost, the total cost (i.e., labor, material, and equipment), and, in the case of time, the total work-hours used, and O is the output or amount of quantity installed (e.g., cubic meters of concrete).

The cost of the equipment is automatically included in the calculation for costs for conventional construction and precast construction. The cost of the equipment for 3Dcp (e.g., robotic arm, concrete pump, concrete extruder and accelerator pump) was proportionally included in the cost of the concrete column using Eq. (2).

$$C_w = Cr \frac{T_w}{T_r} \quad (2)$$

Where C_w is the proportional cost of the equipment included in the cost of printing a single column, Cr is the total cost of all equipment, T_w is the time spent printing, and T_r is the expected lifespan of the equipment.

It is important to note that throughout this study, the costs and time required for printing a geometrically complex column were assumed not to be significantly greater than printing a simple cylindrical column. Therefore, even though the examined 3Dcp project is highly complex, the comparison to building a simple column using conventional construction and precast is assumed as valid. Further, all of the costs in this paper are reported without the overhead and profit that contractors could demand.

3 Comparison of Construction Methods: Examples for a Reinforced Concrete Column

The three types of construction methods considered are conventional in-situ construction, precast (offsite), and 3Dcp (offsite). For conventional construction, the RSMeans cost book [54] was used to understand the crew compositions, equipment, and materials required for all tasks. Based on another source [55], data from the conventional method was used to derive the cost and time of the precast column. Finally, with the help of researchers from ETH Zurich, we report the construction costs and time for printing the columns from the Concrete Choreography project [56].

This study only focuses on the construction of the columns. Thus, the process workflows examined begin with all materials required ready on-site or factory (depending on the scenario), and end when the concrete column is completed in its final location; therefore, in the cases of precast and 3Dcp, transportation from the factory to the site is included. Since the 3Dcp columns were displayed as individual pieces without attaching them to any structural elements, installation costs for the final setup were not considered for the precast column.

To standardize the results, the columns used in this study had the same concrete volume (0.45 m^3) and height (2.7 m). This was based on the information from the Concrete Choreography columns (Fig. 2a). The total concrete volume includes the amount of concrete for the shell and the core. For the conventional and precast columns, the cross-section was adjusted based on the previous parameters (Fig. 2b).

3.1 Conventional Construction

Project Description. The workflow for constructing a reinforced concrete column using conventional construction is shown in Fig. 3. For this study, we only consider the cost and time associated with the construction period. This means that we do not include the time it takes to acquire the materials, design the concrete column, nor to wait for the concrete to acquire structural strength through curing after the formwork is removed. The construction of this column is only theoretical and for a cylindrical shape (Fig. 2b) without any complexity in its geometry.

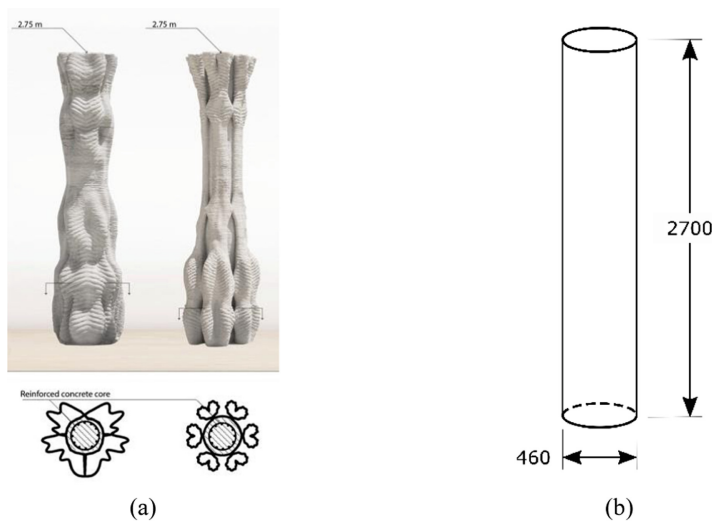


Fig. 2. (a) Columns made for the Concrete Choreography project [57]. Image credit: Ana Anton, Digital Building Technologies; (b) Theoretical columns made using conventional construction and precast (units shown in mm)

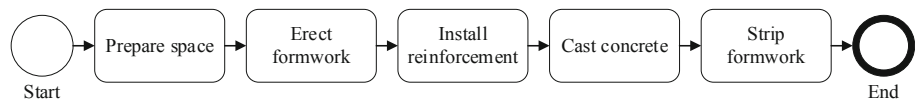


Fig. 3. Construction process of a column built in a conventional way

Assumptions. Although the input data was taken from the industry averages reported in RSMeans, the crew composition for placing concrete was adjusted to account for the characteristics of this example. For example, instead of using eight workers as suggested by RSMeans in crew listing C-20 for a real project scenario, in which several columns are constructed on the job site at the same time, the number of workers for this example was two, and the costs and inputs were scaled respectively. The original crew was shortlisted to include one laborer and one equipment operator. In addition, RSMeans does not provide information for 46 cm (18") diameter column; therefore, linear interpolation for values related to columns with 16" and 20" diameter was used³.

We allocated 0.5 h for preparing the space (e.g., cleaning it, sorting the materials) prior to the erection of formwork. Other assumptions include using steel formwork that can be reused four times, using a prefabricated steel cage for reinforcement (reinforcement material and installation assumed to be the same as for the reinforcement used in the 3Dcp case), and allowing concrete to cure for 48 h before the formwork can be removed^{4,5}. We recognize that for structural integrity, the column must be cured for longer; however, as the main comparison is with the Concrete Choreography columns, which were used for aesthetic purposes, we are not accounting for the typical curing time. In addition, the figures reported in RSMeans for erecting the formwork include the associated costs and durations for making, erecting, stripping, and repairing it as well as the labor to clean the space and move⁶. However, to adjust for the construction of a single column only, 0.3 additional hours were assumed for cleaning the site after the erection of the formwork. Further, it was assumed that stripping the formwork takes 25% of the reported figures. The figures were split accordingly, as seen in Table 3.

Based on the above, the cost of constructing the column is \$774.4, and the total duration, including the waiting time to allow for sufficient curing before removing the formwork, is 50.7 h⁷.

3.2 Precast

Project Description. In general, precast concrete elements are of higher quality than the same elements constructed in-situ. This is because they are manufactured in a controlled factory environment. For the same reason, precast can be seen as a more appropriate comparison to 3Dcp than conventional construction because, at this stage, both are performed in controlled settings. A general workflow of a precast process is shown in Fig. 4.

³ Interpolated between RSMeans 03 11 13.25 3050 and 03 11 13.25 3100 ([54], p. 53).

⁴ Concrete used (4,000 psi, portland cement type I); RSMeans 03 31 13.35 0300 ([54], p. 78).

⁵ Concrete placement taken from RSMeans 03 31 13.70 0600 ([54], p. 78).

⁶ Reference in RSMeans R031113-40 ([54], p. 842).

⁷ 2.7 h for direct time related to the construction of the column; 48 h waiting time before removing formwork.

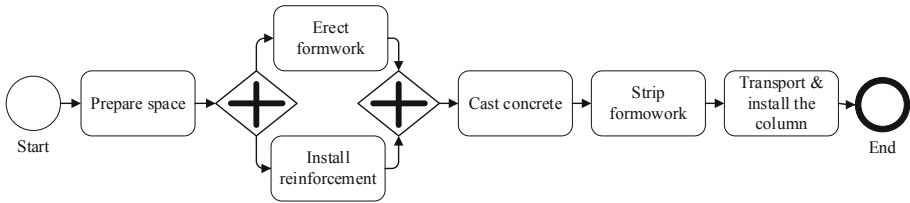


Fig. 4. Construction process of a precast column

Assumptions. It is assumed that the installation of formwork and reinforcement occurs concurrently. It is important to account for the transportation required because the comparison should include the same end product, that is when the concrete column is completed in its final location. A study comparing the costs of different concrete elements [55] reported that precast concrete columns are 21.4% cheaper than in-situ alternatives. Therefore, for simplicity, our research assumes that the cost of the precast column (excluding transportation) is about 80% of the cost of building a column using conventional construction; in this case, \$620. It is also assumed that the cost for machinery required for creating a precast concrete plant is spread across the total number of elements every machine produces and is included in the cost.

Similarly, it was assumed that the construction time for precast is 80% than the one for conventional construction. This reduction factor was only applied to the manufacturing stages, including labor, and the 48 h required for concrete curing were not reduced. Not including the time for transportation of the precast column to its final location, the total time is 50.2 h. Further, it was assumed that a flatbed truck capable of carrying 9,000 kg is rented for 4 h to account for the loading, transporting and unloading durations. The truck rental rate of \$64 per 4 h was obtained from RSMeans⁸. This rate was further distributed among the maximum number of columns such a truck could carry, which was assumed to be 6 (assuming a concrete density of 2,400 kg/m³). Therefore, the proportional truck rental cost was \$10.7, and a wage for the driver of \$182.

Combining these figures, the cost of constructing the column and transporting it to the site is \$812, and the duration, including the curing and transportation time, is 54.2 h⁹.

3.3 3D Concrete Printing

Project Description. The 3D printed column in this example is one of the nine created by researchers at ETH Zurich for the Concrete Choreography project featured at the Origen Festival in Switzerland [56]. The design for these columns was created by students from the Masters of Advanced Studies in Digital Fabrication and Architecture program. The columns were designed using Processing [58], an open-source platform, and further handled by Rhinoceros, Grasshopper, and COMPAS FAB [59] for construction purposes.

⁸ Equipment rental cost from RSMeans 01 54 33 40 7290 ([54], p. 735).

⁹ 2.2 h for direct time related to the construction of the column; 48 h waiting time before removing formwork; 4 h for transportation time to site.

Printer and the Printing Process. The different equipment and the approximate cost is summarized as follows: concrete pump (\$15,000), accelerator pump (\$10,000), and concrete extruder (\$10,000). Other costs were assumed, as shown in the ‘Assumptions’ section below. The printer’s parameters (e.g., print speed), as well as the statistics relevant to the 3D printing of the highly complex concrete columns (e.g., layer height), are shown in Table 1.

Table 1. Printer and printing parameters for Concrete Choreography columns

Printer parameters	Print speed	180 mm/s
	Rate of printing	0.085 m ³ /h
	Max. vertical building rate	3 m/h
	Layer width	25 mm
	Layer height	5 mm
Column-specific parameters	Print time per column	~ 2.5 h
	Print path length	1,600 m
	Printed volume	0.25 m ³
	Total volume	0.45 m ³
	Height	2.7 m

The printer laid out the shell of the complex shape of the concrete column (Fig. 2a). It is worth mentioning that it would be impractical (and probably impossible) to construct the shape of the 3D printed column using conventional or precast methods for time and cost reasons. The 3D printed shell was used as permanent formwork. After the shell was completed, a steel cage was inserted to serve as reinforcement, and the shell was then filled with concrete; however, these columns were not meant to support any loads other than those imposed during transportation and installation. The simplified process workflow is shown in Fig. 5.

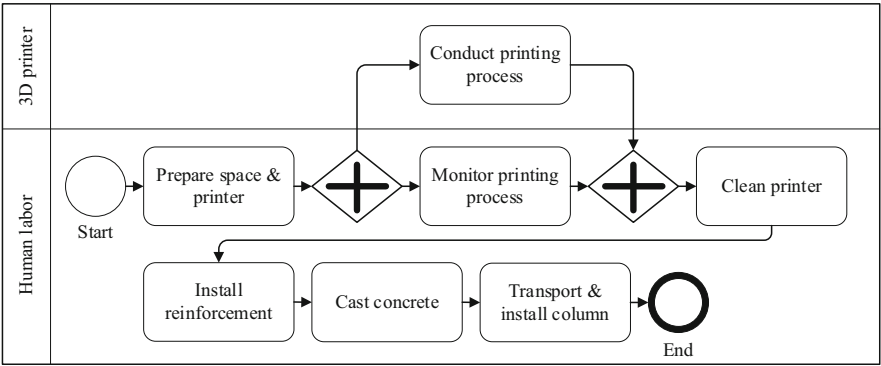


Fig. 5. Construction process of a column built using 3Dcp

Assumptions. The cost of the printer used was assumed as \$125,000 [60], while the cost of the gantry that supports the printer was assumed to be \$100,000. Combining all the costs and using Eq. (2) we obtain that the proportional cost of using the equipment for printing one column is \$32.5. For the calculations, the printing time, T_w , was 2.5 h, and the total service time of all equipment, T_r , was assumed as 10 years [61] or 20,000 h, assuming 8 h of service every business day.

Wages for the workers involved were taken from RSMeans (Table 2). The hourly wage for the 3D printer operator is the only one that is assumed and is equivalent to the salary of the specialty technician used in [35].

Table 2. Hourly wages for constructing a 3D printed concrete column

Crew member	Hourly wage (\$/hr)
Laborer	41.05
Truck driver	45.50
Mixer/material/pump/equipment operator	51.65
Rodman	54.85
3D printer operator/skilled technician	80.00

Transportation was assumed to be the same as for the precast column to limit any variability in the results stemming from sections that are not directly related to 3Dcp.

The breakdown of time and cost of the processes involved in conventional construction and 3Dcp can be seen in Table 3. Precast is not included in Table 3 because the values for it were based on the values obtained from the conventional construction. Similarly, the costs and duration for transportation and installation of the column is only described in the text and not shown in Table 3. In Table 3, L stands for labor, M for material, E for equipment, C for cost, and D for duration. Labor wages are reported for the duration of the entire task unless otherwise specified.

3.4 Results

The time and cost outputs for conventional construction and precast were obtained by adding the respective figures from all steps. For 3Dcp, these figures were obtained by running 1,000 runs in Symphony.NET 4.6 [62, 63] using the Cyclone module to account for the variability in the costs of the equipment and the duration of the tasks¹⁰. A triangular distribution of 20% each way from the most likely scenario (reported in Table 3) was assumed for the duration of all the 3Dcp tasks.

¹⁰ Simulation code available at: <https://github.com/raitispekuss/SymphonyCode>.

Table 3. Comparison of conventional construction and 3Dcp

			Conventional construction	3Dcp
Prep. space & printer	C (\$)	L	1 laborer - 20.5	1 laborer (0.5 h) - 20.5 1 3D printer operator (1 h)- 80
		M	N/A	N/A
		E	N/A	N/A
	D (hr)		0.5	0.5 & 1 for file testing
Erect formwork/Printing process	C (\$)	L	3 carpenters - 72.1 1 laborer - 19.1	2 mixer operators (1 h) - 103.3 2 3D printer operators (2.5 h) – 400 1 pump monitor & material feeder (1 h) - 51.65 1 controller (equipment operator) (1 h) - 51.65
		M	Steel, 4 uses, 18" diameter - 176.2	Consumables - 111
		E	N/A	Proportional cost of the printer, two pumps & concrete extruder - 32.5
	D (hr)		0.45	27.5
Clean site/printer	C (\$)	L	1 laborer - 12.3	3 laborers - 123.2
		M	N/A	N/A
		E	N/A	N/A
	D (hr)		0.3	1
Install reinforcement	C (\$)	L	2 rodmen - 109.7	2 rodmen - 109.7
		M	Cage per column - 200	Cage per column - 200
		E	N/A	N/A
	D (hr)		1	1
Cast concrete	C (\$)	L	1 laborer - 10.7 1 equipment operator - 13.4	3 laborers - 123.2
		M	concrete - ready mix, Portland cement (type I), 4000 psi - 76	Concrete - 38
		E	1 gas engine vibrator & 1 concrete pump - 34	1 gas engine vibrator & 1 concrete pump - 34
	D (hr)		0.26 & 48 before removal of formwork	1 for casting & 24 before transportation to site
Strip formwork	C (\$)	L	3 carpenters – 24 1 laborer - 6.4	N/A
		M	N/A	
		E		
	D (hr)		0.15	

The productivity (Eq. (1)) of each method was calculated using the time and cost. The results are summarized in Table 4. The productivity was calculated for the total examined process (Table 4a) and for cases when the curing time and the final transportation requirement are excluded (Table 4b). Results in Table 4b are a better representation of productivity as they only consider the direct tasks related to the construction of the column.

Table 4. Comparison of the three construction methods

(a) Including curing and transportation						
Row #		Conv. constr.	Precast	3Dcp		
				P	ML	O
1	Time (hr)	50.7	54.2	60.3	59.0	57.7
2	Cost* (\$)	774	812	2,016	1,671	1,340
3	Productivity index** (hr/m ³)	113	120	134	131	128
4	Productivity index** (\$/m ³)	1,720	1,804	4,479	3,714	2,979
(b) Excluding curing and transportation						
Row #		Conv. constr.	Precast	3Dcp		
				P	ML	O
1	Time (hr)	2.7	2.2	32.0	31.0	30.0
2	Cost* (\$)	774	619	1,823	1,478	1,147
3	Productivity index** (hr/m ³)	6.0	4.9	71.8	68.9	66.2
4	Productivity index** (\$/m ³)	1,720	1,376	4,051	3,286	2,550

P-Pessimistic; ML-most likely; O-Optimistic

**Rounded to the nearest integer*

***For comparison across construction methods, a decrease in the productivity index indicates an increase in productivity and vice versa.*

4 Limitations of the Study

Before discussing the results, it is important to highlight some of the limitations of this study. This study is based on the construction process of simple geometry concrete columns. Building columns of increased geometric complexity was not in the scope of this study. This study assumes that the cost and time using 3Dcp are about the same, irrespective of the geometrical complexity of the column. The same cannot be said for the conventional and precast methods. In fact, using these methods to build a column of high geometric complexity would show dramatic differences, to the point that it would be impractical, for time and cost reasons, to use conventional or precast methods for such scenarios. Therefore, the results of this study should not be used to undermine the competitiveness of 3Dcp. In addition, the cost and time required for the design process were not included, yet this process differs among the three methods; digital fabrication methods like 3Dcp can result in more efficiently-produced and sustainable designs. Similarly, we do not account for any post-processing of columns that might be required for the precast and 3D printed columns in case of any misalignments between them and

other elements being installed around or within them (e.g., fenestrations, conduits). Conventional columns do not share this concern as they are manufactured on-site. Another considerable limitation is that the time and cost of the 3Dcp method is based on a research project, still in its experimental phase. It is expected that as the technology matures, the cost of robotic systems and construction material will decrease significantly. Improvement in the overall printing process will also be expected, reducing the overall construction duration. Finally, for a more comprehensive study, it would be required to look at the long-term value of each column, rather than only the cost of construction. This is because 3Dcp offers many benefits (some of them difficult to quantify, such as the aesthetics, customization, etc.) that other methods do not, which would increase the value of 3Dcp elements.

5 Discussion

Based on this study, it was found that conventional construction is the most productive option in terms of the required total construction time (including curing and transportation; rows 3 in Table 4a), followed by precast and then by 3D printing for building a concrete column of simple geometry (e.g., cylindrical shape). Nevertheless, the 3Dcp method was only 16% slower than the conventional in-situ method. This comparison was significantly affected by the curing duration of the casted concrete. For example, in the 3Dcp case, it was allocated 24 h to cure before the transportation to site, while in the other two cases, the curing time of the casted concrete time was 48 h before the formwork could be removed. This discrepancy is justifiable as the casted concrete in the 3Dcp case is enclosed by the printed concrete, which serves as a stay-in-place formwork and has had 24 h to cure before concrete was casted in it.

The conventional column was found to be the most economical per cubic meter, followed by the precast and then the 3Dcp column (rows 2 and 4 in Table 4a). Nevertheless, the difference in unit cost (row 3 in Table 4a) between the conventional and precast columns was about 6%. However, the unit cost for the 3Dcp column was significantly higher, ranging between 73% and 160% over the unit cost of the most affordable option. From Table 3, it can be seen that the greatest cost difference for 3Dcp is the cost of labor during most operations (e.g., prepare printer, printing process, cleaning printer). However, it is reasonable to expect that as automation and the overall printing processes get streamlined, the overall labor cost for 3Dcp will be reduced.

When the curing time of concrete and transportation requirements are not considered (Table 4b), precast becomes, as expected, the most economical and fastest construction method. However, in this scenario, the 3Dcp method is found to be 1,247% to 1,365% more time-consuming than the most affordable option (row 3 in Table 4b). This is because the 3D printed shell must cure for 24 h before future casting can take place, while for the other two methods, concrete can be casted right after formwork and reinforcement have been installed.

The 3Dcp column is 85% to 194% more expensive than the more affordable precast option when transportation and casted concrete curing time are excluded (row 4 in Table 4b). Nevertheless, this increase is not as significant as in the case of time, and as previously indicated, the greatest cost difference between 3Dcp and the other methods

is due to the high cost of labor during the 3Dcp processes, which are expected to go down as the processes are optimized.

Even though the results confirm the expectation that the current costs and time of 3Dcp are higher than for other construction techniques and, hence, the productivity is lower, it should not be inferred that 3Dcp is not worth future exploring. Currently, the material used in 3Dcp is experimental and contains a very high cement content per unit volume. This could be reduced by improving the mix design, increasing the aggregate sizes, and incorporating cheaper and more ecological supplementary cementitious materials. More research and involvement from the industry will certainly drive the costs of the materials down and streamline the process to reduce the construction time.

One potential improvement could be transporting the printed shell to the site before casting concrete in it. This could improve the process as the shell can be moved 12 h after printing yet it needs 12 more hours before concrete can be casted in it. This extra waiting time can occur while the column is transported. Such a change would reduce the total construction time to 55 h and the productivity to 122 h/m^3 . This productivity level is almost the same as the one for constructing a precast column. Other improvements include transitioning to on-site printing if one could protect the printed elements from factors dependent on the surrounding environment and reducing the curing times of both the printed and casted concrete. On top of that, as the cost of robots is decreasing while labor costs are rapidly rising [64], the cost benefits of 3Dcp will become more apparent.

Further, printed formwork currently does not serve a purpose beyond that of a regular formwork. This entails that it could be printed from other materials that do not require long curing times. An example of this is the Batiprint3D project that prints polymer foam as formwork [65]. Nevertheless, future research could allow for printed formwork to become load-bearing and add other functions like becoming a thermal or a durability barrier. This could eliminate the need for casting additional concrete, but will introduce a requirement for post-tensioning or other reinforcement methods. Discussion of such options reiterates that 3Dcp has great potential beyond printing stay-in-place formwork.

It can also be expected that if this study was scaled up and the construction of many columns was examined, 3Dcp would show better comparative results. This is because, as it is done off-site, and it is not dependent on weather conditions, 3Dcp can be more predictable. As in the case of precast, 3Dcp would also benefit from the option to deliver everything to the site during off-peak hours, allowing for more predictable delivery times. Both of these reasons imply fewer chances for unexpected delays as well as human errors, causing potentially costly problems in scheduling. Further, it is possible to print customized elements using just-in-time production to reduce inventories and their associated waste.

Benefits mentioned in this study still make 3Dcp a promising option for cases with unique requirements (e.g., complex geometry) and leave room for future improvements of the technology.

6 Conclusions and Outlook

The goals of this study were to: (1) investigate different construction methods by looking at their processes and use the cost and time involved in each to determine their productivity, (2) dismiss that 3Dcp is already a revolutionary building technique capable of constructing buildings in record times, and (3) argue that 3Dcp has plenty of benefits beyond the cost and time dimensions, and provides other values that are hard to quantify.

It was beyond the scope of this study to analyze the construction costs of building columns of similar complexity to the ones built for the Concrete Choreography project using conventional or precast methods. It is obvious to expect that building columns similar to the 3Dcp ones using conventional or precast methods will significantly increase the complexity and the cost of the formwork, surpassing the costs required for performing the same job using 3Dcp. This could make 3Dcp a more viable option for constructing shapes of sophisticated and unique geometry from the standpoint of costs and time. However, 3Dcp should also be looked at as a potential option for columns of a standard geometry due to different benefits, such as additional functionality that can be printed into the column, topological optimization, geometric freedom, as well as increased transparency during the planning, design, and construction processes.

The challenge of fighting the conservative mindset of the construction industry for implementing new technologies like 3Dcp remains. Factors like the large upfront investment and the lack of concrete normative and building codes, which create extra work (e.g., conduct performance-based testing [66] to be deemed structurally sound), drive up the costs and create uncertainty. Nevertheless, the unique benefits 3Dcp offers must be considered for a full evaluation of this technology, and ongoing research is expected to address them. The cost and time factors will certainly improve with increased interest from academia, industry, and governments. With this in mind, the present work contributes a more sophisticated basis of comparison that can help guide the development and improvement of the 3Dcp technology.

Acknowledgments. This research was funded by the 2019–2020 Post-graduation Research Fellowship Program at New York University Abu Dhabi (NYUAD). The authors would like to express their gratitude to Ana Anton and Dr. Timothy Wangler from ETH Zurich for their comments on the manuscript of this study and sharing information about the Concrete Choreography project. Further, the authors also wish to acknowledge Prof. Benjamin Dillenburger for developing the idea for Concrete Choreography.

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Preliminary Study of the Implications of 3D Printing on the Construction Supply Chain

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Abstract. Construction projects face several challenges, such as budget overruns, project delays, rework, and waste of materials. Most of them are caused by lengthy and complex supply chains involving multiple entities, processes, and interactions. Studies suggest that technologies like robotics, 3D printing, and artificial intelligence have the potential to reduce the complexity of traditional supply chains. In the context of 3D concrete printing, researchers have focused on the robotic systems and suitable construction materials. However, limited attention was focused on the impact on the construction supply chain (CSC). Although studies in healthcare and aviation investigated the implications of new technologies in their supply chains, the outcome cannot be directly applied to the CSC. In addition, studies that assessed the impact of new technologies on the CSC are limited and mostly qualitative. This study addresses this gap by developing a methodology to simulate the implications of 3D printing on the CSC. The methodology adopted contains four elements: 1) Develop supply chain networks, b) Identify input parameters c) Simulate the supply chain networks, and d) Analyze and discuss results. Results from this preliminary study indicate 15.8% and 52.6% lesser entities in CSC-2 and CSC-3, respectively, when compared to CSC-1; a 0.2% and 28.2% decrease in overall effort in CSC-2 and CSC-3, respectively, when compared to CSC-1; and an overall cumulative performance increase of 18.5% and 51.6% in CSC-2 and CSC-3, respectively, when compared to CSC-1. Findings from this study can help construction professionals to understand the implications of 3D printing in the CSC and to assist in easier adoption into the industry. However, caution should be exercised when generalizing to other CSC scenarios or the entire construction industry.

Keywords: Additive manufacturing · Construction automation · Construction supply chain · Digital fabrication · Productivity

1 Introduction

The construction sector is one of the most important key drivers of a country's economy and plays a significant role in the provision of shelter, infrastructure and, employment (Oladinrin et al. 2012). Most often, construction projects involve critical operations and are prone to challenges such as inflation, inefficient planning, changes in

design, the untimely supply of material, legal restrictions, inefficient leadership, unreasonable schedules and, unfeasible productivity goals (Dubois and Gadde 2002; El-Sayegh 2008). However, some of these challenges are expected to be minimized with the advent of new technologies such as robotics, radio-frequency identification (RFID), augmented reality, virtual reality, big data, blockchain and, 3D printing.

Although the construction industry is resistant to adopting new technologies (Oesterreich and Teuteberg 2016), vigorous research is being conducted to analyze the application of these technologies in construction. While many studies are investigating the application of new technologies in construction, the construction industry faces challenges while adopting these technologies due to lengthy supply chains, multiple stake-holders in construction projects, and numerous participants involved. This study tries to particularly investigate the implications of 3D printing on the construction supply chain (CSC).

In several studies, such as Issa et al. (2003), O'Brien et al. (1993), Vrijhoef and Koskela (2000), Behera et al. (2015), and, Xue et al. (2005), frameworks were developed for CSCs that outlined a) the various activities like defining project requirements, planning, procurement of supplies, construction, maintenance, and, demolition, b) participants such as owner, designer, engineer, architect, contractor, sub-contractor, and, stakeholders, and lastly, c) flow of information, funds, and supplies. Due to lengthy CSC involving several stakeholders, the strategic management of the supply chain is critical and indispensable. Akintoye et al. (2000) and Aloini et al. (2012) define construction supply chain management as the tactful management of information, funds and, material across various participants of the CSC to achieve efficiency, and quality-centered products and services.

Although there are multiple metrics to evaluate a construction project, some of the significant ones include duration, cost, quality, safety, productivity, and environment impact (Senouci et al. 2019; Dawood 2010). In this study, the metrics used to evaluate and compare the different CSCs are a) the number of entities, b) the effort involved, and c) the performance of the CSCs. Since the assessment of a CSC is challenging due to multi-level networks (Petrovic 2001), Van der Zee and Van der Vorst (2005) suggest that simulation is one of the most appropriate platforms to model and visualize changes to a supply chain at once. For this study, different CSCs were developed and simulated on Symphony.NET (Symphony.NET 4.6, release Build 4.6.0.316¹), which is one of the most commonly used discrete-event simulation software in construction (AbouRizk et al. 2016).

3D printing application in the construction industry is limited, even though the technology has been in existence for a while (Kothman and Faber 2016). A study by Lim et al. (2012) indicates that 3D printing technology has considerable potential to reduce construction wastes, save material, time and, minimize costs. Alzarrad and Elhouar (2019) presented a study that explored the history of additive manufacturing technology in construction, discussed a few advantages and disadvantages faced during

¹ Symphony is available at no cost for educational and research use (Software Informer 2017). Readers interested in a copy of the last version of the software can contact abourizk@ualberta.ca.

recent applications of this technology, and provided recommendations to overcome the challenges to adoption.

On performing feasibility studies of 3D printing and robotics in construction activities, Elhouar et al. (2019) provided suggestions to facilitate more straightforward automation of current construction tasks. Further, Wang and Skibniewski (2019) investigated the integration of BIM and 3D printing to ensure the timely creation of models for 3D-printing components. Their study suggests that the overall time to create models for 3D printing can be minimized by converting BIM models into 3D printing models. Additionally, this may also facilitate direct modification and printing of the models.

Kothman and Faber (2016) studied the implication of disruptive technologies on the efficiency, environmental impact, and the framework of supply chains. Their work explored how the conceptual CSC varies with respect to the traditional CSC in the Netherlands. A case study was performed to understand the implications of integrating 3D printing into the existing CSC and to conduct a feasibility study of 3D printing concrete in construction. Some advantages, such as elimination of logistics activities, decreased the damage of goods during shipping, complex component manufacturing, and customization of components, were observed based on qualitative analysis.

Several studies researched the technical aspects of 3D concrete printing technology, such as material design, printer design, and component design. However, very few studies investigated the impact of this technology on the CSC. To address this research gap, this study developed a methodology to simulate the implications of 3D concrete printing on the CSC. The supply chain networks developed in this study are inspired by the model presented in Xue et al. (2005).

2 Methodology

The proposed methodology can be divided into four steps (Fig. 1). Each of these steps is explained in the sub-sections below.

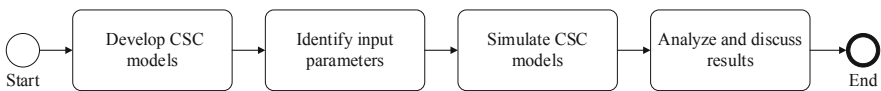


Fig. 1. Overview of methodology for the study

2.1 Develop CSC Models

The fundamental structure and key participants of the CSC models developed in this study are inspired by Xue et al. (2005). Currently, the state of the art of CSC with 3D printing may involve traditional construction practices such as placing conventional concrete over reinforcement bars, the use of traditional reinforcement for tensile strength, or the integration of 3D printed formwork with conventional construction (Apis Cor 2019; Boissonneault 2019). However, as this technology matures, it is

expected that the roles of traditional formwork sub-contractor, reinforcement sub-contractor, and concrete sub-contractor may be significantly reduced, or in some cases, completely eliminated. For example, the main structure may be printed without the use of a traditional formwork; tensile strength may be achieved with the use of fibrous material or a design change, subsequently excluding the need for traditional concrete operations. With more advancement in technology, the number of participants in the CSC may further reduce, where each participant may accommodate and assume multiple roles. However, it is expected that new roles (e.g., programmers, technicians) will be required.

Three scenarios were considered for this study (Fig. 2). The essence of the evolution of the scenarios is inspired by Garcia de Soto et al. (2019). Scenario 1 (Fig. 2a) depicts a representation of the overall current state of 3D printing in the CSC. In the rest of this paper, this is referred to as CSC-1. CSC-1 consists of consultants (general and design), owner, designers (architectural, structural, mechanical, electrical and plumbing – MEP, and, 3D printing), general contractor (GC), sub-contractors (S-Cs) (civil, formwork, reinforcement, concrete, 3D printing, MEP and, finishing), scheduler, project manager and quality specialist. The main phases and elements considered in CSC-1 can be broken down into a) Initiation phase including consulting and review/approval of project demands by the owner, b) Planning and design phase where the lead designer coordinates designs from the architectural, structural, MEP and 3D printing designers, and final design approval by owner, c) Pre-construction phase including coordination by the general contractor, receiving supplies and services from sub-contractors, scheduler, project manager and quality specialist, d) Construction phase, and, e) Commissioning phase including hand-over.

Scenario 2 (Fig. 2b) illustrates the state of 3D printing in the near future. In the rest of this paper, this is referred to as CSC-2. This scenario has the same main phases as those of CSC-1 with some modifications in the pre-construction phase. The main characteristics of CSC-2 are that it does not include sub-contractors for formwork, reinforcement, and concrete operations. Hence, in CSC-2, it is expected that a) the role of the traditional formwork sub-contractor is completely eliminated as it is assumed that the structure is printed without the use of formwork, b) reinforcement is substituted with material/design change, subsequently eliminating the role of the reinforcement sub-contractor, and c) there is no requirement of concrete operations thereby eliminating the role of the concrete sub-contractor. Lastly, Scenario 3 (Fig. 2c) envisions a CSC with 3D printing in which all the services could be provided by a single company able to provide full customization based on the owner's needs (i.e., personalization to meet specific owner's requirements). This implies a high degree of personalization and integration among the different project phases, significantly streamlining the CSC and reducing the number of participants involved. In the rest of this paper, this is referred to as CSC-3. Although this scenario might be exposed to additional risks like knowledge or skills being monopolized by the stakeholders, it may not be a point of much concern.

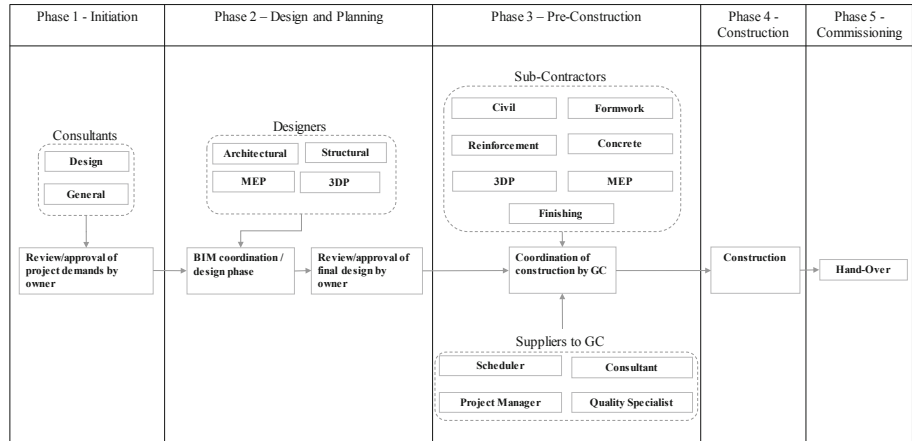
At this stage, it is assumed that the 3D printing technology and required construction materials are matured and that all stakeholders are well-versed with the technology and its limitations. It must be noted that the scenario in CSC-3 is futuristic and positive, and may not show an accurate representation of the future of the technology. However, the study tries to obtain results based on an envisioned ideal scenario. Hence, in CSC-3, it is expected that a) the owner assumes the role of the designer/consultant(s) while outlining project requirements, b) the 3DP designer also takes care of the architectural components of design, c) the owner assumes the roles of the scheduler and project manager, and d) coordinating services and supplies from limited participants rules out the requirement of a general contractor to coordinate construction. In CSC-3, the initiation, design, and planning are considered as an integrated phase (referred to as phase 1), and the pre-construction and construction as another integrated phase (referred to as phase 2).

The models of the different CSC scenarios were created on Symphony.NET. The CSC models developed on Symphony.NET are available on a google drive link (Ramani and Garcia de Soto 2020). The following modules were used: Create – to allow the creation of entities, Task – to process an activity during the simulation, Batch – to batch a group of entities, Unbatch – to unbatch entities, Counter – to keep track of different metrics (e.g., in this study, the entity count and the effort), and Destroy – to destroy entities at the end of the simulation. In this study, the counters are placed at each of the project phases (Table 1(a) and (b)). Entity count refers to the number of entities passing through a given counter (i.e., phase). The performance of the CSCs in this study is calculated at each counter (Eq. 1) and cumulative through the entire CSC (Eq. 2). Equation 1 allows evaluating individual phases (i.e., counters) while Eq. 2 allows for an aggregated view of the CSC as phases progress.

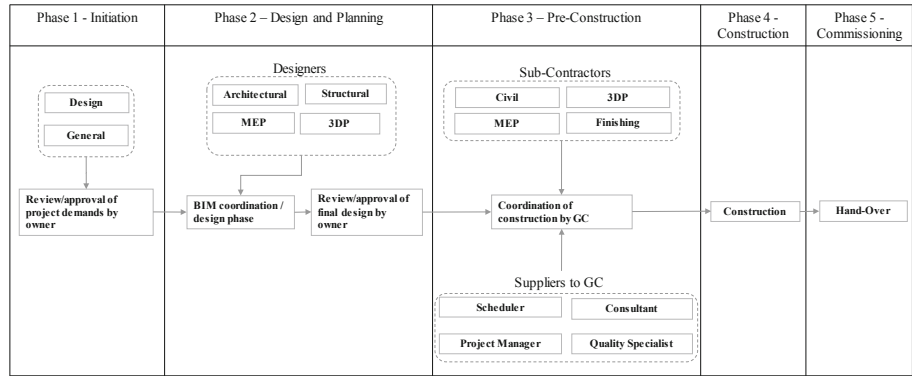
$$P_i = \frac{\max e(PTG)_i + e(IT)_i}{E_i} \text{ where } i \in [1,n] \quad (1)$$

$$CP_i = \frac{\sum_1^i \{(\max e(PTG)) + e(IT)\}}{CE_i} \text{ where } i \in [1,n] \quad (2)$$

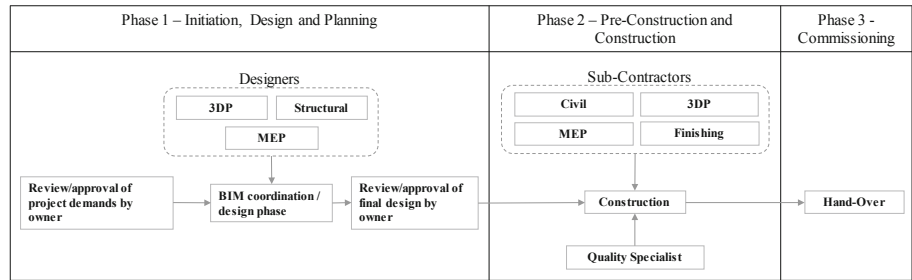
Where, P_i is the performance at counter i , e refers to the effort, PTG is the group of parallel tasks (if any) occurring before counter i , IT is the preceding individual task (if any) before counter i , E_i is the number of entities at counter i , CP_i is the cumulative performance at counter i , CE_i is the cumulative number of entities passing through counter i , and, n is the total number of counters.



(a) Scenario 1: CSC-1 (benchmark)



(b) Scenario 2: CSC-2 (partial integration of different participants)



(c) Scenario 3: CSC-3 (full integration of different participants)

Fig. 2. CSCs considered in this study

Table 1 Estimated effort for tasks for CSC

(a) CSC-1 and CSC-2

Phase	Tasks	CSC-1			CSC-2		
		Min	Max	Mean	Min	Max	Mean
Initiation phase (Counter 1)	Design consulting	3	6	4.5	3	6	4.5
	General consulting	2	5	3.5	2	5	3.5
	Owner reviews/approves/defines project demands	2	4	3	2	4	3
Planning/Design phase (Counter 2)	Architectural design	2	3	2.5	2	3	2.5
	Structural design	2	3	2.5	2	3	2.5
	MEP design	1	3	2	1	3	2
	3D Printing design	1	3	2	1	3	2
	BIM coordination/design phase	2	5	3.5	2	5	3.5
	Review/approval of final design by owner	2	4	3	2	4	3
Pre-construction phase (Counter 3)	GC uses final design to coordinate construction	2	5	3.5	2	5	3.5
	Civil S-C provides supplies/services	1	4	2.5	1	4	2.5
	Formwork S-C provides supplies/services	1	2	1.5	NA	NA	NA
	Reinforcement S-C provides supplies/services	2	4	3	NA	NA	NA
	Concrete S-C provides supplies/services	2	5	3.5	NA	NA	NA
	3D printing S-C provides supplies/services	3	5	4	3	5	4
	MEP S-C provides supplies/services	1	4	2.5	1	4	2.5
	Finishing S-C provides supplies/services	2	3	2.5	2	3	2.5
	GC receives scheduling services	2	5	3.5	2	5	3.5
	GC receives consulting services	2	5	3.5	2	5	3.5
	GC receives project management services	1	4	2.5	1	4	2.5
	GC receives quality assurance assistance	2	5	3.5	2	5	3.5
Construction phase (Counter 4)	Construction	1	4	2.5	1	4	2.5
Commissioning phase (Counter 5)	Facility hand-over	2	5	3.5	2	5	3.5

Note: Minimum and Maximum values are based on authors' experience, information obtained during meetings with industry experts, and literature review

(b) CSC-3

Phase	Tasks	CSC-3		
		Min	Max	Mean
Initiation, Planning and Design Phases (Counter 1)	Owner reviews/approves/defines project demands	2	4	3
	3D Printing design	1	3	2
	Structural design	2	3	2.5
	MEP design	1	3	2
	BIM coordination/design phase	2	5	3.5
	Review/approval of final design by owner	2	4	3
Pre-construction and construction phases (Counter 2)	Civil S-C provides supplies/services	1	4	2.5
	3D printing S-C provides supplies/services	3	5	4
	MEP S-C provides supplies/services	1	4	2.5
	Finishing S-C provides supplies/services	2	3	2.5
	Quality Assurance	2	5	3.5
	Construction	1	4	2.5
Commissioning phase (Counter 3)	Facility hand-over	2	5	3.5

Note: Minimum and Maximum values are based on authors' experience/information obtained during meetings with industry experts, and literature review

2.2 Identify Input Parameters

In this study, the task duration was expressed as the overall effort involved in completing the task. The effort values were assumed to be triangularly-distributed stochastic values (on a Likert scale ranging from 1–7, where 1 refers to the least effort, and 7 refers to the highest effort) with minimum, maximum and average of means based on the authors' experience, information obtained during meetings with industry experts currently engaged in the implementation of 3D printing of concrete in the United Arab Emirates (UAE), and literature from previous studies. The efforts for the tasks considered in this study are shown in Table 1.

2.3 Simulate CSC Models

To account for the variability in the inputs, the simulation for each scenario was run for 1,000 iterations. The cumulative effort (Σe) at each phase/counter, cumulative number of entities (CE), cumulative performance (CP), the effort at each phase (e), number of entities at each phase (E), and, performance at each phase (P) for the three CSCs are shown in Table 2. For the purpose of representation and analysis of results, the values obtained for e, Σe , P, and CP have been rounded off to one decimal place. For estimating the performance at the construction phase in CSC-1 and CSC-2, the entities assumed to be involved in the phase are the general contractor, sub-contractors,

scheduler, project manager, consultant, and quality specialist. Similarly, for estimating the performance at the commissioning phase in CSC-1 and CSC-2, the entities involved are assumed to be the owner, general contractor, project manager, and quality specialist. In the case of CSC-3, the performance at the commissioning phase was calculated based on the assumption that only the owner and the quality specialist are involved.

2.4 Analyze and Discuss Results

This study bases the evaluation of the supply chain on three metrics: a) the number of entities, b) effort, and c) performance. Each of them is calculated discretely at every counter (e.g., E , e , P) and cumulatively at every counter (e.g., CE , Σe , CP). The maximum total number of entities (CE) occurs in CSC-1, followed by CSC-2 and CSC-3. Assuming that the output of each CSC is the same, the lower the number of entities, the better. For CSC-1 and CSC-2, the maximum effort (e) occurs during the planning and design phase (counter 2), followed by the pre-construction phase (counter 3). In the case of CSC-3, the maximum effort is observed at the initiation, planning, and design phase (counter 1), followed by the pre-construction and construction phase (counter 2).

Additionally, maximum performance (P) is observed at the initiation, planning, and design phases for all the CSCs. The comparison of the number of entities, effort, and performance at each counter and cumulative of CSC-2 and CSC-3 against CSC-1 is shown in Table 3. For the purpose of comparison of the different phases, counter 1 in CSC-3 is compared with cumulative values for counters 1 and 2 in CSC-1, and counter 2 in CSC-3 is compared with cumulative values for counters 3 and 4 in CSC-1.

Table 2 Results of the simulated CSCs

Counter	CSC-1						CSC-2						Counter	CSC-3					
	Σe	CE	CP	e	E	P	Σe	CE	CP	e	E	P		Σe	CE	CP	e	E	P
1	7.6	3	2.5	7.6	3	2.5	7.6	3	2.5	7.6	3	2.5	1	12.7	4	3.2	12.7	4	3.2
2	17.6	7	2.5	10.1	4	2.5	17.6	7	2.5	10.1	4	2.5							
3	26.2	19	1.4	8.5	12	0.7	26.2	16	1.6	8.5	9	0.9	2	20.2	9	2.2	7.5	5	1.5
4	29.7	19	1.6	3.6	12	0.3	29.7	16	1.9	3.5	9	0.4							
5*	34.3	19	1.8	4.5	4	1.1	34.2	16	2.1	4.5	4	1.1	3*	24.6	9	2.7	4.4	2	2.2

*Overall results for the CSCs

In the case of CSC-2 vs. CSC-1, no changes are expected in any of the metrics during the initiation and planning/design phases (counter 1 and counter 2). From counter 3 through 5, it is seen that there is an overall decrease in CE , Σe , and e , and an overall increase in CP . At counter 3, CSC-2 shows a 25% decrease in the number of entities, a negligible decrease (0.1%) in the amount of effort required, and a 33.2% increase in performance (P). This can be explained by the reduction in the number of entities (elimination of the formwork, reinforcement, and concrete sub-contractors) involved with the same effort values in CSC-2 as in CSC-1. A similar result is observed at counter 4, which can be explained by a) fewer sub-contractors involved in the construction phase, b) the advancement in technology expected in CSC-2 coupled with

c) the maturity of the concrete printing/construction process. Further, at counter 5, although there is no change in the number of entities and performance, there is a slight decrease (0.2%) in the effort. This can be attributed to the assumption that CSC-2 counts with building codes and regulations that observe 3D printing construction, and the advancement in printing materials and technology. Overall, there is a 15.8% decrease in the number of entities, a 0.2% decrease in the cumulative effort, and an 18.5% increase in the performance of CSC-2 when compared to CSC-1.

Table 3 Percentage change: CSC-2 vs CSC-1 and CSC-3 vs CSC-1

CSC-2 vs CSC-1							CSC-3 vs CSC-1						
Counter	CE (%)	E (%)	Σe (%)	e (%)	CP (%)	P (%)	Counter	CE (%)	E (%)	Σe (%)	e (%)	CP (%)	P (%)
1	*	*	*	*	*	*	1	-42.9	-42.9	-28.0	-28.0	26.0	26.0
2	*	*	*	*	*	*							
3	-15.8	-25.0	0.0	-0.1	18.7	33.2	2	-52.6	-58.3	-32.0	-37.9	43.5	49.0
4	-15.8	-25.0	-0.1	-1.0	18.6	31.9							
5	-15.8	0.0	-0.2	-0.2	18.5	0.0	3	-52.6	-50.0	-28.2	-2.4	51.6	95.2

*No variation (same number of entities, tasks, and efforts for CSC-1 and CSC-2)

For CSC-3 vs. CSC-1, the results show that there is an overall decrease in *CE*, *E*, *Σe*, and *e*, and an increase in *CP* and *P* in CSC-3 compared to CSC-1. Even though the results of CSC-3 may seem overly positive, it must be noted that the results are based on estimated effort values for the different tasks involved in CSC-3, and cannot be directly extrapolated for a different CSC. At counter 1, there is a decrease of 42.9% in the number of entities, a decrease of 28% in effort, and an increase of 26% in performance, which is explained by a) the assumption that the owner assumes the roles of the general and design consultants, and b) the integration of the role of the architectural designer with the 3DP designer. In addition, this increase in *P* can also be attributed to the advancement in the designing process and easier access and availability of commercial software. The pre-construction and construction phase (counter 2) experiences a decrease of 58.3% in the number of entities involved, a decrease of 37.9% in the effort required, and an increase of 49% in performance, mostly due to the integration of roles of the consultant, project manager, and scheduler with that of the owner. Additionally, the maturity of the technology, better awareness of the technology, as well as improvements in material and equipment also contribute to the increase in the performance. The commissioning phase (counter 3) has a reduction of 50% in the number of entities, a decrease of 2.4% in effort, and almost a twofold increase (95.2%) in performance. This can be explained by an easier and quicker commissioning phase due to a reduction in the number of entities involved, established codes and standards, awareness of limitations, and related risks. When compared to CSC-1, CSC-3 experiences a 52.6% decrease in the number of entities, a 28.2% decrease in the required effort, and a 51.6% increase in overall performance.

3 Conclusions

This study can be seen as a preliminary investigation of the implications of 3D printing to the construction supply chain. It presents the results from different simulated scenarios using the current state of 3D printing applications (CSC-1) as a benchmark. Two optimistic scenarios (CSC-2 and CSC-3) were used to compare impacts in terms of the number of entities involved, effort required, and performance. Based on that, the results are promising in the sense that they show considerable room for improvement (e.g., over 50% increase in performance from the benchmark scenario). The most significant improvements were observed due to the capability of personalization provided by 3D printing, the integration of different phases, and advancements in the materials and technology coupled with support from building regulations and industry standards. However, it must be noted that caution should be taken considering the results of the simulation as they cannot be directly generalized to assess the evolution and implication of 3D concrete printing in other CSC scenarios or the entire construction industry.

Although many of the optimistic views adopted can be supported due to the vigorous research that is taking place regarding 3D printing technology itself and the materials used, the reader should be aware that the CSC-2 and CSC-3 scenarios are based on theoretical assumptions that are overly positive. Some of the limitations of this study are related to the inputs used (e.g., effort vs. time and cost), which should be addressed by measuring different tasks in a real project setting, and the limited range of performance metrics considered for the evaluation of the construction supply chain developed. In addition, ongoing research focuses on examining the task efforts in real-time with the help of a case study and considering an additional range of performance metrics such as lead time, supply chain cost, supply chain efficiency, and environmental impacts. In conclusion, this study can inspire future work to focus on the implications of new technologies on the construction supply chain, better help construction professionals to make a rational decision about which technology to use, and facilitate its implementation.

Acknowledgment. Special thanks are given to the industry experts who met with the authors to provide their opinion on the different stages of 3D printing of concrete, in particular in the UAE. Their information was used for the definition of tasks and estimation of required efforts.

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Applications and Case Studies



Fast Complexity: Additive Manufacturing for Prefabricated Concrete Slabs

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Abstract. Although slabs are major concrete consumers, they are mostly flat, oversized, monolithic boxes with significant embodied energy. The state of the art shows how computational design can lead to structurally efficient, light-weight, functionally integrated, and aesthetically accomplished slabs. However, these non-planar geometries are fabricated using complex formwork solutions involving multiple digital fabrication processes and manual concreting.

This paper puts forward a novel fabrication method for the construction of materially lean concrete slab systems using two different Additive Manufacturing (AM) processes: Binder Jetted (BJ) formwork and 3D Concrete extrusion Printing (3DCP). A reusable formwork is fabricated first, using the BJ, and the loadbearing part of the slab element is then directly 3D-printed on top. This method combines the essential advantages of the two fabrication techniques: the high precision of BJ and the higher fabrication speed characteristic to 3DCP.

The described 3DCP process uses a *set on demand* concrete that is activated inline, immediately before leaving the extruder-tool. A technical innovation is identified in dynamically varying the amount of activator for changing contour length.

Keywords: 3D printed slab · Concrete extrusion 3D printing · Binder jetting · 3D printed formwork · Structural optimization · Set on demand

1 Introduction

In the past decade, digital shaping of concrete has developed significantly, aiming to increase the productivity and reduce material consumption in the construction industry. The implied economic and ecologic benefits of these developments are proportional to the significant market share and carbon footprint of the concrete industry. In particular, for architectural applications, the biggest potential lies in optimizing slabs, which represent 85% of the weight and cost of a concrete structure in multi-story buildings [1].

In this context, this paper reports an automated method of concrete placement for the production of lean material slabs that are easy to assemble and optimally combine structure and function (Fig. 1). With the aim of decoupling geometric freedom from the cost of concrete elements, this research investigates multiple AM methods to find a

straightforward fabrication workflow for shaping concrete slabs as part of an automated process that minimizes formwork requirement.



Fig. 1. View towards the soffit of the final prototype covering a surface of 2 m^2 (1 m by 2 m); Photo: Axel Crettenand, Digital Building Technologies, ETH Zürich

2 State of the Art

Currently, cost-effective slabs are planar. Either monolithic or with unidirectional hollow cores, the shape of slabs is dictated by the cost of formwork, which considerably exceeds the cost of concrete. Materially optimized slabs usually require bespoke formwork solutions that come at a very high cost due to the one-time use. As such, they are often a premium product for structures for which slab weight is an important factor.

2.1 Bespoke Slab Systems

Bespoke slab designs can achieve better functional integration, new aesthetics, structural performance, and material efficiency [2]. On the one hand, complex geometries can integrate precise heating and ventilation ducts, enclosures for electrical conduits and fire sprinklers, as well as smart assembly interfaces. Integrated services bypass the need for additional suspended ceilings and reduce clutter for attractive architectural concrete soffits.

On the other hand, topology optimization algorithms can distribute material in the most efficient spatial configurations for minimizing deflections under the given design load-case. Weight reduction can indirectly lead to further material savings in the vertical structure and foundations, thus additionally decreasing the embodied energy of buildings.

Such functionally integrated and material-efficient slabs can be easily modeled in a digital environment, but their complexity poses fabrication challenges.

2.2 Formwork for Bespoke Slab Systems

Reusable flat-panel formwork systems are efficient and compatible with most architectural floorplan requirement, but not suitable for curved or structurally optimized geometries. The choice of mass-produced formwork systems for ribbed or waffle slabs is limited. For uniformly distributed orthogonal grids, voided Biaxial Slabs use plastic containers to create large voids inside concrete slabs, while Perforated Holodeck Waffle Slabs further integrate services through continuous voids transversal to the structural members.

Volumetric slabs usually require complex formwork solutions involving multiple digital fabrication and concreting processes, as exemplified by the Smart Slab (SS) [3] and by the Functionally Integrated Funicular Slab (FIFS) [4], both from ETH Zürich. SS featured an articulated soffit on the underside, a twisted grid of variable-height upstand structural ribs on the topside, and a spatially curved network of internally post-tensioning ducts. BJ 3D printing was used for the underside, laser-cutting for the topside, and FDM 3D printing for the internal post-tensioning mounting brackets. Concreting was done in two stages, with the soffit side being sprayed, and the topside being cast. FIFS featured a similar articulated soffit and network of upstand ribs, but pushed the complexity even further with the integration of structural voids and a bespoke network of ventilation air ducts, within the depth of the concrete slab. The fabrication used FDM 3D-printed formworks for the soffit and internal ducts and laser- and hot-wire-cutting for the structural ribs and voids.

The wide range of disconnected digital fabrication processes involved alongside conventional manufacturing in the production of a single building component is not feasible for commercial use on a large scale. The complex supply chains and complicated assembly sequences imply risks and liabilities that are incompatible with the realities of the building industry. To address these challenges, direct digital fabrication through 3DCP could bypass the need for complex formworks altogether.

2.3 3DCP on 3D Support

3DCP has already been used for the fabrication of architectural scale components, but with several exceptions, almost exclusively for the in-situ printing of walls [5]. Recent advancements in the processing strategies for 3DCP have resulted in the prefabrication of concrete formworks for columns, which are filled with fibre reinforced concrete [6] or reinforced with standard rebar cages [7].

Several fabrication challenges regarding the integration of reinforcement and cold joints between layers have limited the application of this technology in load-bearing slabs, which need to resist considerable bending stresses. However, two completed examples of entirely 3DCP horizontal load-bearing structures have been realized.

The bicycle bridge produced by TU Eindhoven uses a concrete filament reinforced with a continuous steel cable [8]. The modules, assembled in a line, are held in compression by the main reinforcement system of post-tensioning cables.

The pedestrian bridge fabricated at the Tsinghua University School of Architecture, has modular hollow compression only bricks assembled on a temporary scaffold [9].

Confirming the limited fabrication space of 3DCP, the transfer of loads between the components of both bridges is made through planar interfaces that coincide with the orientation of the layers. Furthermore, the layers remain visible, thus creating a pattern of vertical lines, customary to 3DCP.

From a design perspective, geometric limitations and concrete surface quality are the main drawbacks associated with 3DCP. In particular, the limited overhangs restrict the fabrication space to predominantly vertical extrusions, while the filament remains visible, creating a stepped low-resolution pattern, on the surface of printed elements. In an attempt to break away from the horizontal constraint of layers, alternative methods of material deposition were explored. Robotic extrusion onto a support was speculatively used in the creation of small-scale prototypes [10]. Even if it is catalogued as a method to increase the geometric freedom of 3DCP [11], its applicability in real buildings is held behind by required tolerances in complex geometric assemblies.

3 Methodology

A design research and experimental methodology was used to determine the necessary fabrication sequences. The present chapter describes the building system, formwork manufacturing, automation of concrete deposition and the reinforcement strategy.

3.1 Slab Building System

The design research follows the development of a construction system suitable for AM methods. Similar systems were pioneered in the 1960s by Pier Luigi Nervi [12], but they were geometrically limited by the conventional flat formwork panels. The proposed system is based on the same modular prefabrication principle of Nervi, but relies on BJ and 3DCP to enhance its flexibility, to integrate advanced features, and to locally customize the geometry for further optimization.

The proposed method was tested on a 2 m² prototype, which represents a 1:1 excerpt of a larger slab. The prototype investigates the design and manufacture of a two-way joist or waffle slab, prefabricated in discrete elements that are mechanically assembled through post-tensioning. The joists are hierarchically differentiated in principal ribs, which are 50 cm deep and span the long side of the slab, and secondary ribs, which are only 35 cm deep. The interstitial surface is a shallow, 20 mm-thick vaulted concrete shell. For additional stiffness, the shell is articulated with a network of minor ribs that follow the principal stress lines and provide a distinctive aesthetic for the soffit.

The discretization into independent nodes follows the modular pace of the joists (Fig. 2a) that are subsequently pre-assembled through longitudinal post-tensioning in beam elements. These elements are delivered on site and cross-post-tensioned during assembly (Fig. 2b).

The prototype demonstrates the prefabrication of two independent 1 m² concrete modules reusing the same formwork (Fig. 1). The fabrication in small modules has several advantages. Mainly, a small module system is very flexible and the necessary 3D-printed formwork is minimal and can be efficiently reused. Furthermore, the small

modules are suitable for small fabrication facilities with limited build volumes or for on-site factories. While the reusable 3D-printed formwork defines a repetitive surface that is identical for each module, the 3DCP structure above is differentiated for each module, with the possibility of optimizing structural dimensions for an efficient static behaviour. Furthermore, functional voids can be dynamically integrated into bespoke locations in each module (Fig. 2b).

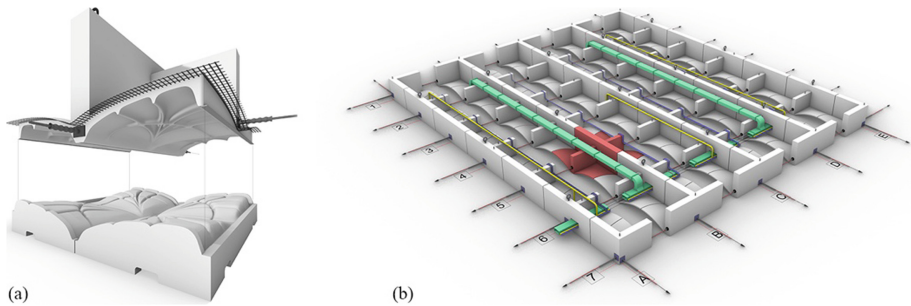


Fig. 2. Fabrication sequence: (a) the fabrication of one node module and (b) the assembly of modules in beam segments and slabs.

3.2 BJ Formwork

BJ is an iterative 3D printing process in which thin layers of sand are selectively bonded with an organic binder injected through a printhead, replicating a digital model in consecutive horizontal sections. Once the process is complete, the loose sand particles are mechanically removed, leaving behind the clean bonded-sand object. The resulting objects have a limited direct use in architecture due to their relatively low compressive strength of 8.6 MPa [13]. However, this is enough for the fabrication of formworks for slabs of 60 cm in thickness that can only generate hydrostatic pressures in the range of 15 kPa.

BJ technology is commercially available in volumes of up to $4 \times 2 \times 1 \text{ m}^3$, and horizontal resolutions in the range of 100 μm . However, the formwork for the prototype was discretized into much smaller parts for ease of handling. The 3D printing time for the formwork, including the post-processing steps was of 24 h, but larger volumes come with significant economy of scale.

The two 0.5 m^2 formwork parts are fitted with upstand lip edges for clean interfaces between adjacent concrete elements. These are limited to 25 mm in height to prevent collisions with the robotic end-effector and to facilitate demoulding. Recessed details for the integration of architectural finishes are included. These allow the tolerance-free integration of shadow gap details at the interfaces between formwork parts and concrete elements. Finally, referencing details and lifting handles are integrated into the formwork to enable positioning and assembly.

The soffit has a demoldable geometry with no undercuts. To this extent, as well as to ensure a smooth concrete surface, the porous surface of the formwork in contact with the concrete was post-processed. A fast-curing two-part thermosetting unsaturated polyester coating was applied in a specific volume of 3 L/m² in three layers with 50 min curing time in between. The priming layer sealed the permeable sand object, penetrating its surface down to a depth of 3 mm. The finishing layer was a wax-enriched polyester flowcoat, ensuring a durable, waterproof, and glossy surface for a high-quality concrete finish. Finally, a separation layer using a water-based release agent is applied immediately before the concreting process. This enabled a smooth demoulding process 24 h after casting. The formwork can then be immediately reused with minimal maintenance required: the surface was rinsed with water and the release agent was re-applied.

3.3 3DCP Technology

The 3DCP process was developed interdisciplinary at ETH Zürich, and employs a two-component system consisting of Ordinary Portland Cement (OPC) mortar and Calcium Aluminate Cement (CAC) paste. The two materials are intermixed immediately before extrusion, or set on demand [14, 15], thus ensuring the required early age structural build-up [16].

The dedicated hardware for 3DCP is composed of two commercially available progressive cavity pumps and a custom extruder-tool able to actively intermix the OPC mortar with the CAC activator. Both pumps are positioned outside of the printing area and are manually supplied with material. Their input and output signals are integrated into the robot controller and monitored through the robot user interface, allowing them to be switched on and off and their flow-rate to be monitored and adjusted online.

The kinematic system consists of an ABB IRB 4600 six-axis robotic manipulator suspended on a three-axis Güdel gantry. Specific to this application, the kinematic system can ensure a large print area as well as different orientations of the extruder-tool in relation to the geometry of the formwork.

The mortar formulation consists of calcareous crushed sand with a maximum grain size of 2 mm (solid volume fraction 46%), OPC (CEM I 52.5R) at a water to cement ratio of 0.4, 8% substitution of microsilica, and 15% substitution of limestone powder. A superplasticizer is dosed at 0.7% by weight of binder, sucrose as retarder prolongs the open time to 6 h, and a commercial thickener gives the initial yield stress. The accelerator consists of a Ciment Fondu[®] (CAC) paste, retarded with 0.1% sodium gluconate, stabilized with 0.1% commercial polyethylene glycol, and with a 0.27 water to cement ratio.

The technical innovation described in this paper is to dynamically vary the amount of activator during printing, between 1.5% and 10% CAC to OPC weight ratio, by changing the flow rate of the activator pump. Initially, a fluid concrete mix activated at 1.5% fills the fine details of the support surface. As the height progresses, the layer length decreases; thus, the amount of activator increases up to 10% to compensate for the shorter print-time of one layer.

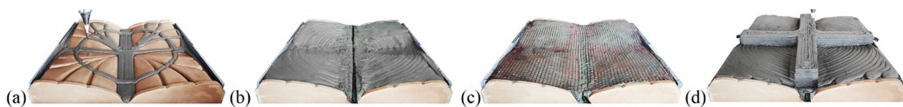


Fig. 3. Fabrication sequence: (a) filling the main ribs; (b) inserting the post-tensioning tube for the main beam; (c) adding the CFRP mesh after the first layer; (d) printing the main ribs.

Through its on-demand hardening, this two-component system can make the transition from digital casting to 3DCP into a continuous automated concreting process. Lasting a total print-time of 60 min/m^2 , the automation of concrete deposition is solved with three print-path sequences (Fig. 3a, 3b, and 3d). The first three layers of concrete describe a surface-like geometry, which inherits the precision of the formwork and constitutes the visible soffit, while subsequent layers describe the structurally-efficient bi-dimensional grid of beams, that require no additional formwork.

3.4 Reinforcement

In the absence of a reinforcement strategy compatible with the 3DCP process, this paper proposes a project-specific solution. The solution combines a secondary reinforcement for shrinkage cracks mitigation through a Carbon Fibre Reinforced Polymer (CFRP) mesh, with a primary reinforcement through post-tensioning steel tendons.

The reinforcement is added in three different stages: a tube for the post-tension of the main beam (Fig. 3b), a CFRP mesh (Fig. 3c), and a tube for the post-tension of the secondary beam. The corrugated tubes used to guide the post-tension cables have an inner diameter of 15.1 mm. A 16 mm by 10 mm grid CFRP mesh with a thickness of 0.5 mm is placed after the first surface-covering layer of concrete.

With a thickness of only 20 mm, the vaulted surfaces in between the main ribs have one continuous inter-layer reinforcement. The advantage of placing the reinforcement during the concreting phase is the positioning accuracy on a double-curved geometry. Therefore, the laborious step of including temporary spacers, as done in the case of concrete casting, is improved. However, some measures were taken to avoid collisions between the robotic end-effector and the inserted objects. The layer following the CFRP mesh were increased from 5 mm to 10 mm in height. Furthermore, if collisions do occur, the 3D-printed nozzle of the extruder-tool is made of a strong, yet flexible nylon, which can bend without breaking.

4 Fast Complexity – Discussion and Outlook

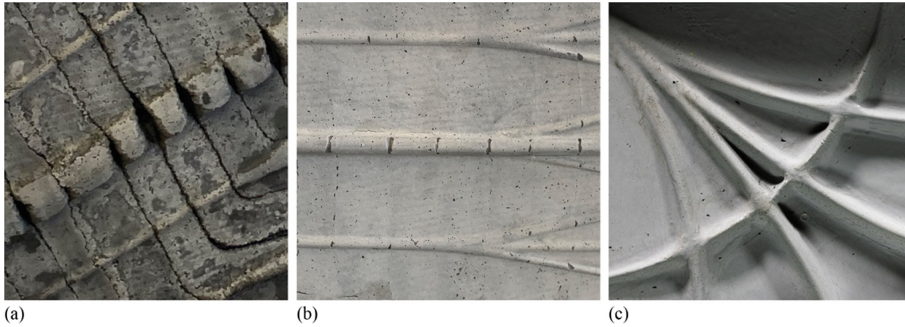


Fig. 4. Soffit surface quality: (a) high-viscosity concrete and print-path crossing the geometry of a rib; (b) fluid concrete and print-path crossing the geometry of a rib; (c) fluid concrete and print-path following the geometry of a rib;

The resulting prototype (Fig. 1 and 4c) exhibits a soffit surface of superior quality compared to 3DCP. The surfaces are smooth, similar to cast samples, with only faint discolorations or superficial imperfections indicating interfaces between extruded layers. Based on empirical observations, these imperfections can be significantly reduced if the first layer of concrete is very fluid when extruded. Additionally, by overprinting - i.e. by extruding more material and creating a pressure zone in between the formwork and the nozzle - the concrete layer interfaces can be further homogenized.

Visual assessment of the prototype further highlights a direct relationship between the shape of the formwork, the print-path and the quality of the concrete surface. Independent of the viscosity of the 3DCP filament, for accentuated cavities inside the formwork, inter-layer traces remain visible (Fig. 4a and 4b). This situation is mitigated through the custom print-path that follows the main geometric features of the formwork (Fig. 3a and 4c).

The reinforcement requirement is met by the addition of discrete elements during printing. Initially aiming to solve the fabrication sequence, this prototype didn't benefit from structural calculations. Nevertheless, proper structural dimensioning and structural testing are essential and will be an integral part in future investigations. Moreover, the ribbed ornamented pattern can be integrated as part of the structural concept and dimensioned accordingly.

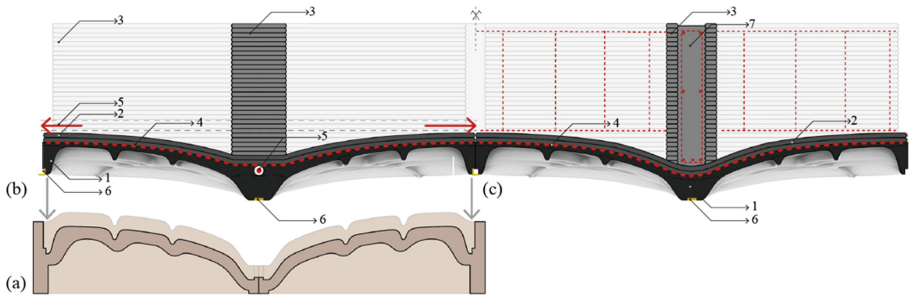


Fig. 5. Sectional diagram showing possible reinforcement solutions (a) BJ formwork; (b) fully 3DCP segment reinforced with 3DCP mesh and post-tensioning cables; (c) 3DCP reinforced with CFRP mesh and integrated formwork for main beams, cast in-situ with reinforced concrete. 1-3. 3DCP layers of concrete, with 1.5% CAC, 5% CAC and 10% CAC; 4. CFRP reinforcement mesh; 5. Post tensioning tendons; 6. Brass L and I profiles for joint detailing; 7. Reinforced concrete cast in-situ.

3D printing the beams as solid elements was not equally successful (Fig. 3d and 5b). Even if 3DCP is fast, it cannot compete with the fabrication speed and structural performance of cast concrete. This is why, for future implementations, only the outer contour of the ribs can be 3D-printed, as a formwork instead of printing the full rib (Fig. 5c). Consequently, the system will become lighter during transportation and will work similarly to a Filigree Wideslab method, in which the beams are cast in-situ with conventional reinforced concrete.

This fabrication method allows for extensive morphological variation. The process is based on using different fabrication resolutions. First, 3D printing of high-resolution formwork shapes the most detailed part of the slab that is apparent in the inhabited space. Even if the formwork can be reused, the strength of the process lies in the possibility to customize and replace the formwork as the design requires. Next, 3DCP is used to infill the formwork and to create the outline of the ribs. Finally, the structural part is potentially finalized through casting. The different fabrication resolutions are unified through the use of a single process: 3DCP. In this sense, all the AM processes are used selectively for what they are best at, optimizing the fabrication speed, but still delivering high quality complex surfaces.

5 Conclusion

The proposed approach efficiently combines two distinct AM methods in a process that targets the production of optimized slabs.

In the context of AM formworks, which involve complex supply chains and intricate manufacturing sequences with multiple processes, the proposed method simplifies fabrication effort by limiting the use of formwork to the visible areas of a slab. Only these apparent surfaces require high quality and precise finishes. In contrast, for the hidden and interior parts of the slab, the high resolution of digitally fabricated formworks is unnecessary, hence the rough aesthetic of the fast formwork-free 3DCP is adequate.

Given the rapid throughput of the 3DCP technology, which often lacks the precision of cast concrete, the proposed approach sets a new standard for geometric complexity and level of detail achievable for directly 3DCP architectural building components.

Using a fraction of the material in a conventional slab, the proposed fabrication method can significantly reduce the embodied energy of concrete elements. From a sustainability perspective, this is an example of material efficiency because the structure integrates functionality and building services within its structural depth. Additionally, the soffit needs no additional finishing layers or dropped ceiling systems. Furthermore, the high-quality apparent concrete soffit provides new design solutions in a robust and durable surface that needs minimal maintenance throughout its lifecycle.

The proposed method allows the implementation of radically new aesthetics in slabs with functional features on both sides. Moreover, the method involves less digital fabrication processes, requires less manual labour, and is more resource-efficient in comparison to state of the art fabrication alternatives for bespoke slabs. Based on these considerations, the method aims to facilitate a more diverse repertoire of contextualized design solutions in real buildings, an often overlooked aspect, but essential to sustainable construction.

Acknowledgements. This research was supported by the NCCR Digital Fabrication, funded by the Swiss National Science Foundation (NCCR Digital Fabrication Agreement #51NF40-141853). We acknowledge the contribution of Philippe Fleischman to the development of the ABB robot user interface for the 3DCP process in the Robotic Fabrication Lab, ETH Zürich. We also thank our colleagues and partners for their support: Eleni Skevaki, Yoana Taseva, Tobias Hartmann, Matthias Bernhard, Pietro Odaglia, Axel Crettenand from Digital Building Technologies, Andreas Reusser and Achilleas Xydis from ETH Zürich and Stefan Miesel from BASF Master Builders Solutions.

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Architectonic Explorations of the Possibilities of 3D Concrete Printing: The Historic Building Fragment as Inspiration for New Applications with 3D Concrete Printing in Architecture

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Abstract. The scope of this one-year research, carried out within a graduation studio consisting of 16 students, was to explore how this novel technique can lead to the development of new architectural forms. The graduation-studio called ‘De Centrale Gent, with 3D Concrete Printing’ explored the technique of 3DCP within the historical city of Ghent and through researching, designing and testing by printing.

Fase 1: We investigated what the application of this technique could mean for architecture itself, taking the historical facades of the city of Ghent as an inspiration for the development of new printing techniques in 3DCP. We focused on developing a design-‘instrumentarium’ that is specific for the concrete printing technique, as well as on techniques that could push the boundaries of the so far known possibilities in shape, materiality’s, and ornamentation with Concrete Printing in relation to architecture. The research aimed to discover new aesthetic and sustainable qualities in 3D-printed manufacturing, through 5 main topics: light, joints, and patterns, supporting material, and assembling. The research was developed at the Eindhoven University of Technology and the prints were made with the 3DCP in the laboratory of the faculty of the Built Environment.

Fase 2: Printing prototypes: A selection of results and findings of the one-year research in the graduation studio have been elaborated and collated into a new final product and summary design for three columns, featuring new aesthetic possibilities in 3DCP. The three columns were printed and exhibited at the DDW 2019

Keywords: 3DCP · Research by design · Architectural design · Heritage · Fragment · 3D concrete printing · Robotic arm · Molds · Facades · Complex shapes · Ornament · 3DCP columns

1 Exploring Architectonic Expressions in 3DCP

1.1 Contemporary Craftmanship with 3DCP

Many of our cities have a legacy of buildings with richly ornamented facades. The value of heritage buildings is translated in the form of designations of protected

townscape or monument status. These buildings represent a time when craftsmanship reigned supreme and facades were ornamented with sculpture and carvings. Today's high labor costs mean that this ornamentation and complex formal language can only be realized in very exceptional cases. The 3DCP makes it possible to realize complex shapes and ornamentation, as the printing process makes complicated formworks and labor-intensive machining processes superfluous. The question we asked ourselves is how a contemporary interpretation of the historical architecture of the city of Ghent could be made and translated into new designs with 3D printed concrete as a novel technique. Furthermore, the question we also asked ourselves is which designs and processes are specific to the technique of 3D concrete printing and thus developing a novel material specific aesthetic architectural vocabulary.

1.2 3DCP and the Challenges of Reinterpreting Heritage Buildings

Ghent, in Belgium, flourished in the Middle Ages thanks to its fabric industry, and in its harbor. Nowadays, some remnants from the industrial revolution period are concentrated in the vicinity of the docks and are currently designated as cultural heritage structures, such as the former electricity power plant. The latter was the focus of a one-year graduation studio, consisting of 16 students and 4 supervisors. We researched on the possibilities for the revitalization of this building and its immediate environment and studied how it could transform into a new cultural hotspot for the city of Ghent, using 3DCP. Together with the research into the history and heritage, an intensive exploration into the application of the technique of 3D printing was integrated. Elements of the design resulted in actual 3D printed parts, so contributions in design and hands-on work with the 3D printer were done regularly.

The graduation studio involved close interdisciplinary 'research by design' collaboration between two departments from the faculty: Architectural Urban Design Engineering and Structural Design. Focus was to apply the available technique of concrete printing and adapt it locally to the historic context. The historic city of Ghent was studied, redesigned, and then a part of the city was reinterpreted, using 3DCP. Following a careful and meticulous analysis of façades in the existing historical context, and its historical façade fragments, students were asked to reinterpret these using the technique of 3DCP and translate that into new architectural designs. Prototypes and fragments of these designs were 3DCPrinted in the laboratory, scale 1:1.

Our studio contribution to 3DCP thus involved connecting the regeneration of existing buildings, with the identity of the new-built, intertwining these, and connecting them to the existing historical surroundings.

1.3 Working Method

The goal of the design studio was to allow research, design and experimentation with the 3DCPrinter to go hand in hand, so that findings from printing could be incorporated directly into the design and possibilities could be tested. This "design by doing" method made that the possibilities but also the impossibilities of the material and the technique could be experienced at first hand and could be converted into proposals that

directly apply to the specific properties of the material. At the same time, we could learn from the process and search for new hands-on solutions.

The first starting point was to fathom the possibilities and constraints of the printer and the material. The angles of inclination that could be printed, the straitjacket of the continuously printed line, and the limitations due to gravity and the curing process of the material. For this purpose, an extensive research in state of the art of the technique and literature was done.

The second starting point was that the students had to learn to work with the printer: from cleaning the printer to mastering programs that allow parametric modelling such as Grasshopper and Rhino in order to draw 3D models.

Finally, the students formed groups and researched specific themes.

In order to research the meaning of 3DCP for architecture, the technique itself was researched along 5 parallel individually themes: 3DCP and transition/light, 3DCP and joints, 3DCP and textures, 3DCP and support, and 3DCP and assembly. The following research addressed possibilities of the concrete print technique in transition with other materials, by experimenting the introduction of 'lights' by means of glass-fibers, into the printed material; the application of various types of joints with 3DCP; various achievable textures and ornamentation of 3DCP; the technique in relation to its support materials and molds; and 3DCP and its possibilities for assembly. In this way the possibilities and impossibilities of the 3DCP technique in relation to architecture were investigated. The findings were elaborated into a designs that were printed by the students.

The "Making of Architecture", the direct relationship between design and the realization of a tangible object is one of the key ambitions of our chair of Architectural Design and Engineering. By letting students experiment directly with the material and the printer, the relation between material, detail and design became concrete. The close collaboration with the Unit Structural Design, made the design trajectory multidisciplinary, an indispensable feature to truly understand the possibilities of 3DCP.

2 Fase 1: The Research Themes

2.1 5 Themes

As described above, students set out their research explorations in various teams. In the group-based research, the following list of themes was set up, whereby each group focused on a particular topic related to 3DCP:

- Transition
- Connection
- Patterns in nature
- Support
- Assembly

Given these topics/key words, the students came up with a further definition;

a - Transition – combining materials - concrete & light

Multimateriality and the potential of working with different materials was studied and the possibilities of creating a translucent concrete were tested. Glass fibers were introduced in the concrete, thus creating a translucent effect when lights were set on the surface. The glass fibers were in first instance put manually in the concrete. In a later stage a device could be developed that inserts the fibers in the concrete during the printing process.

The result was a concrete artefact that lights up when lights are placed on the inside, thus creating a glowing effect. The glass fibers guide the light through the concrete and give the concrete a translucent effect (Fig. 1).

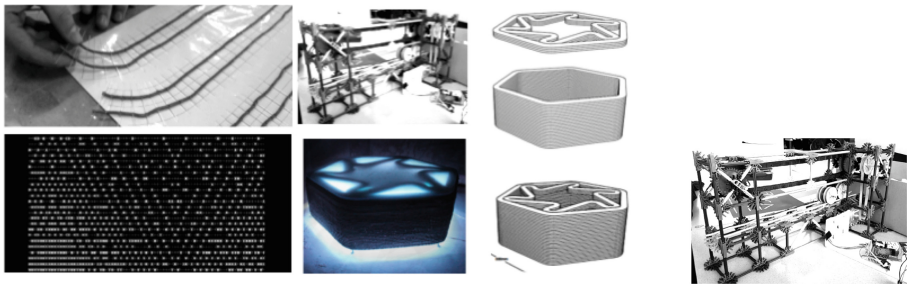


Fig. 1. Transition: prototype design, fiber mats and pattern, placing fiber test driving unit (Credits images: Alessia Biffi, Jory Rijvers, Roy Soons)

b - Connection – optimization – 3DCP and flexibility

The subject of the research was the connection and how two printed concrete objects can be connected to each other. In addition, the question was how 3DCP-elements can be attached to adjacent elements of different materials, such as window frames, doors, floors and walls. Different kind of joints were examined exploring fixed and flexible joints (Fig. 2).

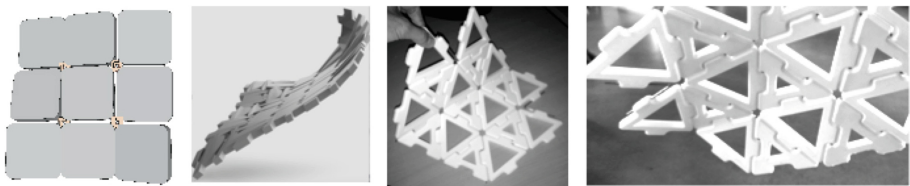


Fig. 2. Connection: joints hinge system with hollow tubes inserted during printing proces Credit images: Daniëlle Grolleman, Michel Martens, Andrea Zambotti.

c - Patterns in nature – finding textures and study structural properties

The technique of 3d printing lends itself perfectly to printing different patterns. The patterns from nature have served as a source of inspiration. In this research various techniques and print paths were investigated to develop patterns. In the research techniques such as printing, and CNC milling were combined (Fig. 3).

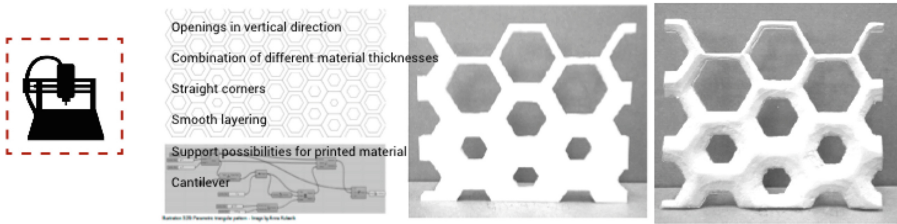


Fig. 3. Patterns: current 3DCP limitations, cnc milling. Credits images: Sander Colen, Anna Kulawik, Jon Scherptong

d - Support – testing support structure and double curved design

An important aspect in the use of concrete is the formwork and the way the liquid material is poured into a mold. By investigating new techniques of support, the possibilities of casting complex forms were explored. A range of formwork materials has been tested, ranging from more traditional materials such as sand and gravel to more experimental materials such as printing in glass beads, gel, liquid clay and yoghurt. The results were promising, as double-curved surfaces, overhangs and flowing round shapes became possible. For the Artefact the technique with glass beads was taken as casting material. Because the material tended to collapse after a number of printing layers, a system was devised to print the concrete in a crate, whereby the crate is raised during printing. The crate is continuously filled with glass beads during printing. The result of the research was a free form vase, in which the limits of manufacturability were explored. In the future we expect a lot from the process of printing in liquid materials, where strictly speaking full 3D printing becomes possible and the limitations of gravity can be tackled (Fig. 4).



Fig. 4. Support, complex shapes and 3DCP: printing in a box with glass-beads (Credits images: Remi Bogaert, Rik Bollen, Michael Yuen)

e - Assembly – testing discreet assembling and sequence

The group's research focused on how different fragments can be printed and assembled. The research was twofold: on the one hand it focused on the development of complex geometries that could be printed, on the other hand it focused on the way in which the individual elements could be assembled and interlocked to form a larger whole (Fig. 5).

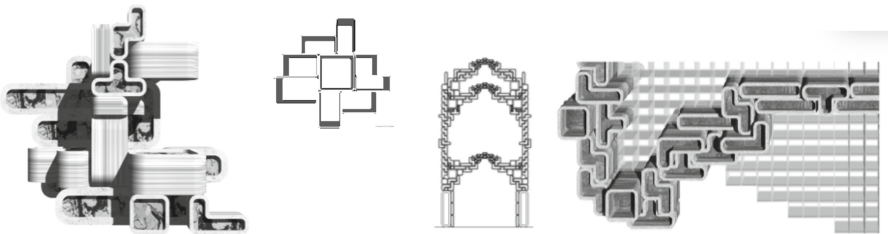


Fig. 5. Assembly: façade fragments, basic shape simplicity, interlocking elements Credits images: Rick Abelen, Rukiye Galeli, Sinan Önder, Celil Sahin.

2.2 The Continuous Line

In order to be able to propose designs that follow the inherent logic of the printing process it is necessary to understand it and use it as an ingredient of the design. One of the key features of 3DCP is that the printing always follows a continuous uninterrupted line. Starting from the current research on 3D printing, an algorithm was created to solve one of the biggest issues surrounding the technology: creating a printable pattern using a continuous path. Currently it is not possible to stop printing and start the print in a different place. All the objects need to be printed using a continuous path. Taking into consideration the structural requirements, a pattern was generated using an algorithm. Hereby it was important that it had to be suitable for the 3DCP: it had to be ensured that the curve is continuous, that there are no overlaps, but also it was needed to consider that the distance between each point in the curve follow the restriction of the printer (the dimension of the nozzle) and that angles are rounded. These requirements were met by using algorithmic models that are based on mathematical functions such as circle relaxation and the Travel Salesman problem. The first ensures that during the printing process there are no accumulation of material (especially not in the corner path).

Through a system of vectors, the circumferences are moved in order to fill the entire surface and not overlap each other. The centers of the circumferences are used as points to be connected using Travelling Salesman algorithm, which connects them ensuring no overlapping and the shortest distance possible. The development of this algorithmic model was a long process composed of different steps that used small, 3D-printed prototypes in order to understand the limitations and potential of the design steps (Fig. 6).

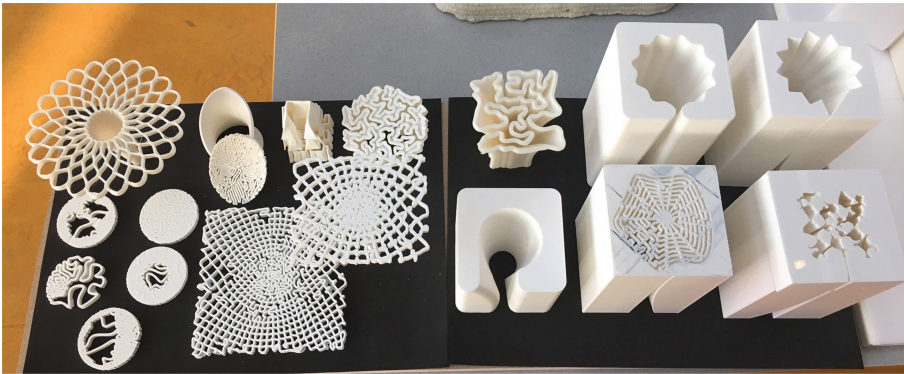


Fig. 6. Printed patterns: exploring possibilities with 3Dprinting utilizing a parametric model (Credits images: Alessia Biffi)

With the algorithm a surface is filled in with a single, uninterrupted line, whereby the density and angles are parameters that can be adjusted, according to the established requirements. In this way new aesthetics of ornamentation are created when translated into a printed object.

The pattern can change by varying different parameters. The advantage of utilizing a parametric model in the design is the ability to create different patterns and ornaments that will answer to the specific requirements of the printed objects. All of them are created by the same algorithm.

3 Fase 2: The Design and Printing of 3 Prototypes

3.1 3D-Printed Columns: The Manufacturing Process

After one year of designing and printing within the graduation studio, arose the need to create one or more objects where the various findings and results could come together in one finished, elegant object, that exhibited the various discoveries.

The project for 3 columns: “3D-printing Architectural expression” is a final product showcasing the findings of the graduation studio. The design was made after the final presentations and made by Alessia Biffi under supervision of Juliette Bekkering and Sjeff van Hoof. The columns were printed by the firm Vertico. The design of three columns arises as a way to show new aesthetic qualities reachable through 3D-printing techniques. This was made possible thanks to two main discoveries that were found during the graduation course:

- By varying the print path during the printing process, it is possible to create on the surface of a printed object, different patterns.
- Through the use of supporting material free-form shapes and big inclinations and overhangs are possible. The columns design is the result of a parametric model realized using Grasshopper + Rhino (Fig. 7).

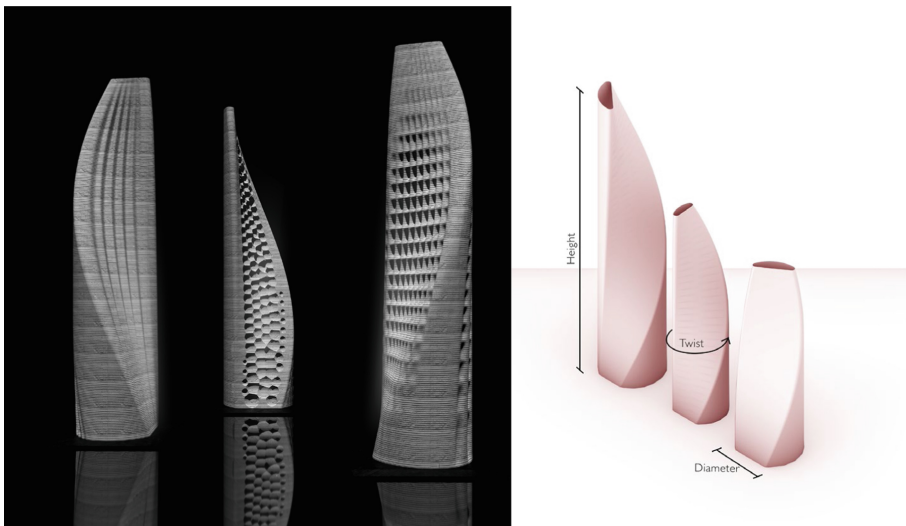


Fig. 7. The columns are designed parametrically: by twisting different parameters (such as height, rotation, diameters), different designs can be created.

The creation of a script and parametric model allowed us to easily and fast create variable parameters, such as the height of the columns, the amount of twist in each, and the diameters of the objects. The twisting shape of the design was dictated by the ambition to show that it is possible to print concrete with a significant overhang (Fig. 8).

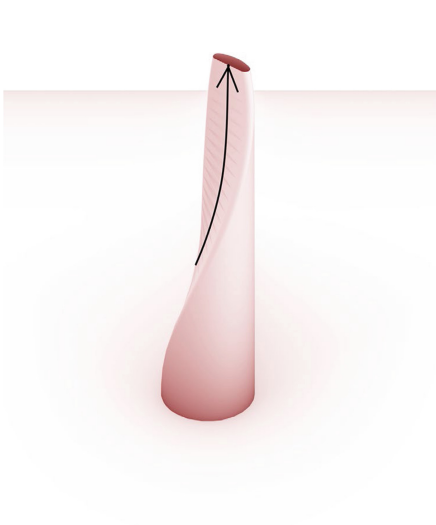


Fig. 8. The design shows a significant overhang

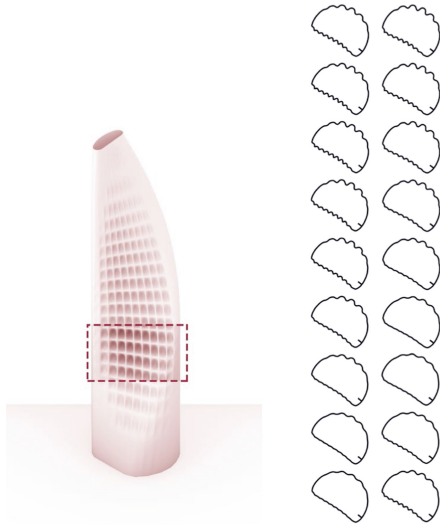


Fig. 9. Varying of the printing path in order to create different patterns

This is an additional challenge compared to polymer printing. The patterning on the columns was created by varying the printing path. The use of Grasshopper was fundamental in this step. Varying each layer in a specific manner allowed us to obtain in the overall columns a specific pattern that is characterized by repetition, changing of depth, and fading. The use of a parametric model was essential in order to obtain all different layers that together form the desired pattern. By tweaking these parameters three patterns were created: Lines, Snakes, and Hammer columns.

Once the models were ready, the manufacturing process started. Vertico, a 3D-printing specialist company, realized the columns. Through the use of a 6-axis robotic arm, high-resolution details were achieved.

The manufacturing process involved the use of glass beads as supporting material. The columns were sliced in 3 parts, each one approximately 1 m. This was necessary for transporting the columns from one location to another. Each piece was printed inside a wooden box that could increase in height by adding additional elements on top of it. This was fundamental in order to contain the glass beads used as supporting material for the concrete.

Slicing of the Columns: The Printing Process

Once the columns have been designed, the following phase is to make them printable. The printing time of these columns, including testing time, was ten days in total. During these days, together with the team of the company Vertico, we had to ensure that the 3D model was adaptable into a code. An additional script was used to slice the model, along the z axis, into layers which resulted in closed curves (Fig. 9).

Each curve was subdivided into points which were characterized by specific properties (orientation, x-value, y-value, z-value, etc.). Utilizing this data, the robot re-traced the 3D model.

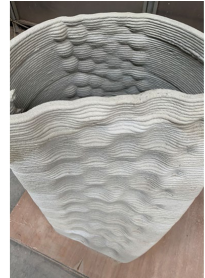
Different tests were made in order to print the columns without supporting material. The experiment shows that after a few layers (15 layers), the object started collapsing, as the first concrete layers were not hard enough to support the additional weight. Thanks to the research achieved through the graduation project regarding the use of 3D-printing utilising supporting material, we were able to continue with the process and print the columns. During the graduation studio different cantilever degrees were tested as well as different materials as supporting material. We discovered that printing with material such as grain as a temporary support structure also effected the structure of the concrete and the texture of the printed object. As the pressure of the printed object on the support structure is higher the influence of the texture on the printed object becomes more visible (Fig. 10). The choice of using glass beads due to their low density and their minimal effect on the texture of the concrete. In addition, they were easy to remove from the concrete once it hardened.



Fig. 10. 3D printing experiment without a box



Fig. 11. 3D printing experiment using a box to contain the supporting material and removing the glass beads



Each element was printed inside of a wooden box, with the purpose of keeping the supporting material in place, offering a foundation for the wet concrete. Once the printing starts inside the box, supporting material is added around the printed layers. Once the printed object reached the height of the box (Fig. 11), we waited 30–45 min to allow the concrete to harden, before placing a second box on top of the previous and continuing the print. Once the printed structure has hardened (24 h) and can support itself, the support structure was then removed and used for printing other sections of the column.

One day after the objects were printed, it was possible to remove the supporting material. Due to the relatively lightweight of the prints, the supporting material did not imprint much, allowing for easy removal.

Each piece is roughly 1 m tall, with the heaviest weighing 100 kg, and their printing thickness was 20 mm. alongside the manufacture of the columns, steel structures were designed to fit inside the columns in order to satisfy the safety requirements of the DDW. Via the use of a parametric model, the steel structure was designed with branching arms that connect the central pole with the internal perimeter of the columns.

The columns were displayed at the Dutch Design Week in Eindhoven 2019, in Strijp-T (Fig. 12).



Fig. 12. Exhibition at the Dutch design week 2019

4 Conclusion

The final product and the research done during this project shows the enormous variety of possibilities that the technique of 3DCP has to offer and the beautiful results that can be achieved. Highly detailed patterns were realized, and significant overhangs were printed. The research shows that there is still a wide field to be explored in order to investigate which new aesthetic qualities can be created with 3D concrete printing. New patterns and ornamentations can be developed and a whole new architectural language of complex free forms is possible. The research was limited to the use of only concrete, but new research can be done into combining different materials and techniques within

the printing process in an automated way. Research at the Eindhoven University of Technology already shows some attempt in combining different materials with 3D printing concrete, such as glass marbles and optical fibers. These were previously done by manually placing the material during the printing process and could be furthered by investigating how to automate this process. An important new step will be to translate the results of the research into new applications in the built environment. The research shows that this is only the tip of the iceberg and that a huge field of possibilities is there to be explored.



Acknowledgements. For this article, use has been made of the information, research and visual material bundled in the graduation research report: “3DCP, Graduation studio Ghent”. 2019, Made by Rick Abelen, Alessia Biffi, Remi Bogaert, Rik Bollen, Sander Colen, Rukiye Galeli, Daniëlle Grolleman, Anna Kulawik, Michel Martens, Sinan Önder, Jory Rijvers, Celil Şahin, Jon Scherptong, Roy Soons, Michael Yuen, Andrea Zambotti., graduation students in Architecture, Eindhoven University of Technology (2019) (graduation reports can be downloaded from the TU/e library) and Barbara Kuit, Juliette Bekkering, Sjeef van Hoof, Zeeshan Yunus Ahmed. “Architectural Design with 3Dconcrete Printing TU Eindhoven, Exploring the future”, Materi-Art, to be published 2020.

Credits. All drawings, models, renders and photos made by: students studio Ghent.

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A Robust Mortar and Printing System

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Abstract. In this paper the motivation and the choices for a mortar that is being used in the print factory jointly owned by Weber Beamix and BAM is discussed in general. Attention will be given to the choice of binder for the mortar. The results obtained during quality control from a large project will clearly show that with this mortar concept monolithic objects can be obtained with no influence of the printing direction on the parameters measured (compressive strength and flexural strength). Also some results from interfacial fracture toughness measurements will be presented. These results also indicate the formation of monolithic material. Results of durability tests (frost/thaw de-icing salt resistance) will be presented showing that this material is safe to use in outdoor applications. The printing system with an in-line quality monitoring system of the fresh mortar will be presented. The modifications of the mixing unit have led to a finely controlled water dosage during the mixing step of the mortar. With the in-line sensor, measuring the yield of the pump, the viscosity and the density of the pumped mortar, it has been possible to implement a feedback loop to the water dosage and to the yield of the pump. The yield of the pump is very important especially when layers adjacent to each other are required to form a monolithic structure. With the feedback loop of the viscosity measurements to the water dosage it has been possible to print with this mortar with a very low water dosage over long periods of time (6–8 h.) and still not having issues with blockage of hoses etc.

Keywords: 3D concrete printing · Robust · Mortar · In-line quality control · Feedback control system · Monolithic

1 Introduction

As building material producer we have seen many developments aiming at making the building of houses and the manufacturing of infrastructural projects more efficient. Nevertheless, the labor productivity of the construction industry has not increased in the last decades. Therefore, when the TU-Eindhoven started the research on 3-D concrete printing, now about 5 years ago, and was looking for industrial support we as Saint-Gobain Weber Beamix gladly joined the consortium supporting this research. During this program most of the experiments were performed with material supplied by us.

During the research project some members of the consortium decided that it would be beneficial to put the knowledge acquired at the TU in practice by printing a small bridge (the bridge in Gemert). For Weber Beamix this was the starting point to start

thinking about starting our own printing factory with a dual purpose; to put the knowledge acquired by the TU-Eindhoven into practice by manufacturing 3-D printed concrete for commercial projects and secondly to develop the technology further especially with regard to robustness of the system.

To this end Weber Beamix together with BAM opened in January 2019 their commercial print facility in Eindhoven.

2 3-D Concrete Printing System

2.1 Recipe of the Mortar

For the additive manufacturing with concrete one is facing the challenge of stacking layers of freshly prepared concrete or mortar on top of each other with the following pre-requisites:

- In an automated system the automated freshly prepared mortar must be transported from the place of preparing (mixing) to the place of deposition. This is preferably done by pumping the mortar through a hose. In other words, the freshly prepared mortar must be pumpable;
- When stacking one layer on top of the previous layer the bottom layer should not give way (collapse) but should be able to carry the layers being put on top;
- The challenge of being able to stack layers on top of each other can be solved in two ways. Either one chooses to have a fast setting/hardening system in such a way that when the next layer is being deposited the first layer has already set. This can be achieved by having quick setting/hardening mortar recipes or by adding accelerator to the mixing water at the mixing stage or also by adding an accelerator at or close to the print head. The second option is to optimize the rheological behavior of the fresh mortar in such a way that the fresh mortar has a yield stress that is large enough to make this feasible and additionally make the mortar shear thinning (thixotropic) to allow for the pumpability of the fresh mortar.

For the development of our mortars we choose to go for a normal setting behavior of the mortar based on traditional and well known binder systems combined with a strong thixotropic effect. Amongst others this gives the following advantages:

- In case of a calamity in the process the mortar does not immediately harden in the hose;
- A well know behavior of the final material with regard to durability aspects(frost, frost/thaw de-icing salt resistance etc.). “Rules” with regard to water/cement ratio in relation to durability and strength development would also largely apply to this system;
- A much easier obtained monolithic structure; by stacking layers on top of each other it has to be safeguarded that the structure as a total can be considered as being monolithic;
- A good availability of the raw materials in remote areas.

With this in mind the recipes that were developed comprised the following raw materials:

- Ordinary Portland Cement, OPC (CEM I 52, 5R);
- Limestone filler (to adjust for the fineness of the mixture and help in pumpability);
- River sand (max particle size 1 mm);
- Additives; rheology modifiers to obtain the required thixotropic behavior and plasticizers to obtain a low water/cement ratio in order to safeguard durability and strength development.

During the development stage a number of mortars mainly varying in water demand have been developed.

2.2 Printing Setup

Within Weber Beamix we have a long experience with the dry-mortar technology supplier M-Tec. We therefore choose to start off with the standard M-Tec equipment. Our first experiments were conducted with Duo-mix 2000 system. It took not long though that we realized that for printing commercial projects a bagged system is labor intensive and rather messy. Therefore, for the print factory it was decided to implement a closed silo system from M-Tec (SMP-system; Silo Mix Pump). The silo system was in house adjusted with regard to the specific requirements of the 3-D concrete printing system.

Amongst others the following modifications were implemented:

- Change in water dosing system (digital);
- Change in pump capacity, the original rotor/stators were replaced with the lower capacity rotor/stators from the Duo-mix system;
- The sensor systems for starting and stopping the mixing were altered;
- The mortar reservoir above the pump has been altered to have a better agitation of the mortar in this reservoir;
- The pump outlet was redesign to prevent blockages.

For positioning the print head at the proper position we have chosen for ABB as the supplier. In order to be able to print larger objects we have put the robot on a track. So for the positioning system we have a IRB7600-325_3.10 robot with a IRBT 7004 11 m track.

Depending on the kind of object to be printed we have a choice between a round nozzle and a rectangular nozzle. Printing with the round nozzle is rather straight forward and easy to do but also has its limitations. For printing objects for load bearing purposes we often choose for a rectangular nozzle that allows us to feed a wire into the printed layer. By doing so the structure is reinforced in one direction. Here the printing becomes more complicated because the speed of the movements of the robot not only have to be aligned with the yield of the pump but also the feeding of the wire into the layer of mortar that is being deposited has to be in line with the speed at which the robot is moving. On top of this the rectangular nozzle always has to be exactly aligned with the layer that is being printed. For curved objects this implies that the nozzle has to turn depending on the curvature of the object that is being manufactured. This turning

requires an adapted feeding system of the mortar to the nozzle. To be able to print the biggest objects possible an extension to the robot arm is needed. With this, the rotation of the nozzle required an additional axis of the robot.

2.3 Robustness of the Printing System

For small tests and development studies the robustness of the system is of minor importance but for commercial application it is required that the printing system can be run with preferably one operator. With the present installation a typically print speed is about 15 cm per minute with a layer width of approximately 70 mm and a layer height of 10 mm. When printing larger objects with a total weight of approximately 4 to 5 tons this requires a printing time of around 8 h. This requires a robust system with constant properties (rheology) of the fresh mortar and a constant yield of the pump. Especially when load bearing constructions are printed in which adjacent layers also have to contribute to a monolithic construction this characteristic becomes essential. To this end a sensor (patent applied for) has been incorporated in the pumping line.

This sensor measures:

- The pressure in the line (bar);
- The amount of mortar transported (kg or liter per hour);
- The viscosity of the mortar conveyed (cP);
- The temperature (degrees Celsius);
- The density of the mortar (kg/m^3);

From the amount of mortar conveyed a feedback to the frequency controller of the pump has been implemented. This safeguards that during the printing of an object the amount of mortar required is really being pumped guaranteeing that even for adjacent layers in the structure monolithic behavior is obtained.

The results of the viscosity measurements are fed back to the water dosing utility guaranteeing a constant viscosity and workability of the mortar during a longer period of printing.

As an extra safety precautions upper and lower limits of yield, viscosity and pressure with light and sound signals have been implemented. In the case of an unusual event and malfunctioning of the feedback systems or any other problems this alarms the operator and allows him to take over the control manually and by doing so can prevent the loss of an object that has almost been finished printing.

3 Printing Control: From Wet Mortar to Hardened Concrete

3.1 In-Line Measurement and Control System

Most of the printing in the print factory is being done with the Weber 3D 160-1. As explained before both the yield of the pump and the viscosity of the pumped mortar is analyzed during pumping and adjusted as to guarantee proper quality of the extrusion and of the final element.

All the data is collected by a dedicated data logger allowing future verification of specific print sessions (quality control). Figure 1 gives an example of the operator view of the automated system. In case of need the operator can override the system within certain limits to avoid ruined prints or blocked system components.

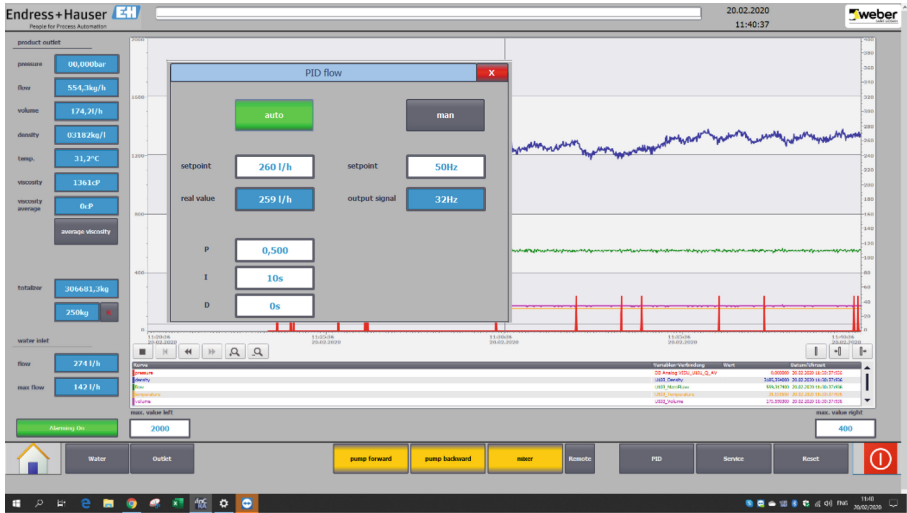


Fig. 1. Operator view of the feedback and QC system.

3.2 Mechanical Properties of Printed Elements

During a period of 4 months all the print sessions in the print factory were submitted to a rigorous QC test. Prior to start printing an element and after a finishing an element test samples were printed. From the test samples prisms ($4 \times 4 \times 16 \text{ cm}^3$) were cut to measure the mechanical performance. The aim of this endeavor was to make sure that the efforts with regard to automation (constant yield of the pump and constant workability of the mortar) would result in a monolithic hardened material with a constant performance. Besides the prisms were also cut in such a way that conclusions could be drawn with regard to the anisotropic character of the hardened material (effect of print direction on the performance of the hardened concrete).

Additional tests were performed during or after this test phase to provide additional information of the mortar characteristics. The extra performed tests were: shrinkage; creep; E-Modulus; adhesion between layers.

Flexural and Compression Test

From the test samples the prisms were cut in different directions with regard to the print direction as indicated in Table 1. The samples were cured at print bed conditions during 28 days and tested according the EN 1015-11:1999. The results are showed in Table 2.

Table 1. Mechanical properties test directions.

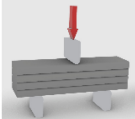
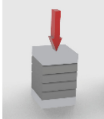
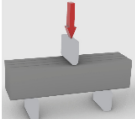
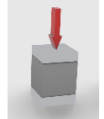
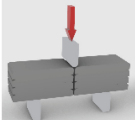
Test direction	Description	3-point flexural test	Compression test
A	Force application perpendicular to the print direction		
B	Force application aligned with the print direction		
C	Force application perpendicular to the print direction (force applied in the joint between 2 adjacent layers)		
S/C	Force application aligned with the print direction in a sample extracted from a vertical section		-

Table 2. 28 days mechanical properties test results.

Test direction	Flexural strength			Mechanical strength		
	Average	Std. dev.	N. samples	Average	Std. dev.	N. samples
A	10.1 MPa	1.4 MPa	165	56.0 MPa	5.5 MPa	330
B	10.2 MPa	1.4 MPa	165	54.3 MPa	5.8 MPa	330
C	10.0 MPa	1.4 MPa	162	57.1 MPa	5.6 MPa	324
S/C	9.64 MPa	0.2 MPa	3	—	—	—

The tests performed clearly show that the mechanical properties of the printed objects do not depend on the print direction vs load application direction. And clearly show that the hardened material is homogeneous. Even when the load is applied between 2 adjacent layers the average result is similar. The test direction S/C samples were tested as a last confirmation with the samples available.

Shrinkage and Creep Tests

During one of the print session in the mentioned period, samples were cut out of a wall element to perform shrinkage and creep tests. This tests were performed by our internal lab and/or by the TU/e [1].

The shrinkage tests were performed by measuring the length variation of the sample between 1 and 91 days. The measuring direction was the direction of usual load application in a structural element. The results are showed in Table 3.

Table 3. Shrinkage test results.

Measured by	91 days		
	Average	Std. dev.	N. samples
TU/e	1.0 mm/m	0.01 mm/m	6
Weber Beamix	1.0 mm/m	0.31 mm/m	3

The creep tests were performed on specimens extracted from the same wall by measuring the length variation of the sample between 28 and 91 days under an average load of 8.76 MPa. The results are presented Table 4.

Table 4. Creep test results.

Measured by	91 days		
	Average	Std. dev.	N. samples
TU/e	1.0 mm/m	0.03 mm/m	6

E-Modulus

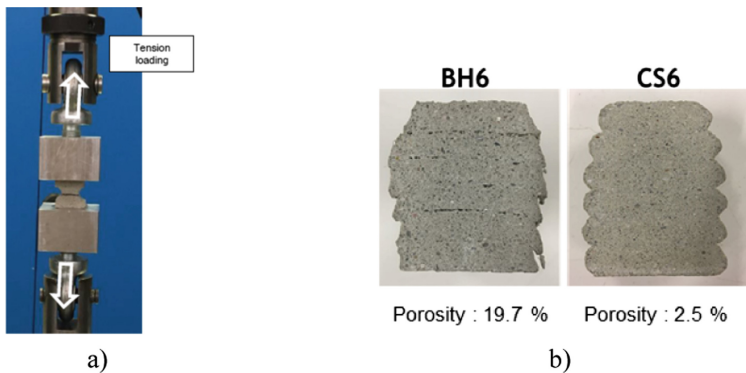
The secant E-Modulus was determined from the load vs deformation results of the compression tests performed after 91 days, according the NEN-EN 12390-13:2012. The result achieved was 30 GPa.

Bond Between Layers

Two different type of tests were selected to evaluate the bond between layers: pull-off test and DCDC test (Double Cleavage Drilled Compression). The first one measures the tensile interfacial strength and the second one the interfacial toughness. Both tests were performed by the team of Saint-Gobain Research Paris [2].

Pull-off Test

For this test it was decided to prepare the samples with a dog-bone shape in order for the failure to occur at the desired position. In Fig. 2 the setup and the samples used for test are shown, in Fig. 3 the results of the test are given.

**Fig. 2.** Pull-off test setup, a) and tested samples, b).

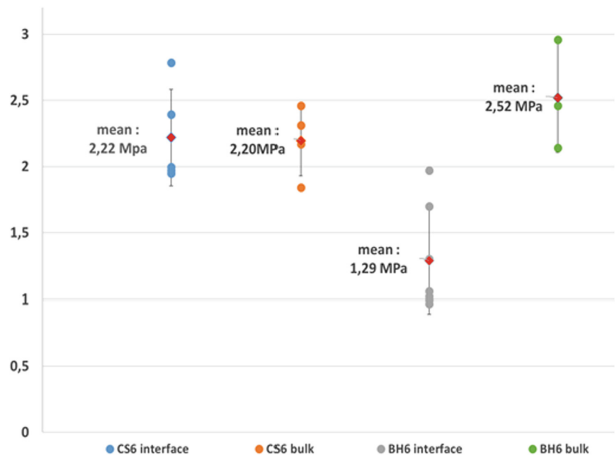


Fig. 3. Results of the pull-off test.

The results of the pull-off strength test are very dispersed with a maximum standard deviation of 35% (BH6) due to the porosity at the interface. Nevertheless it is obvious that for the sample with normal porosity values there is no difference between the characteristics of the bulk and the interfacial layer indicating that we have monolithic material.

DCDC Test

In this test the same type of samples as in the pull-off test were analyzed. In order to perform the experience in the interface or bulk material, the position of the DCDC centering was selected. The samples were submitted to a compression load and the crack propagation measured with an optical imaging system, see Fig. 4.

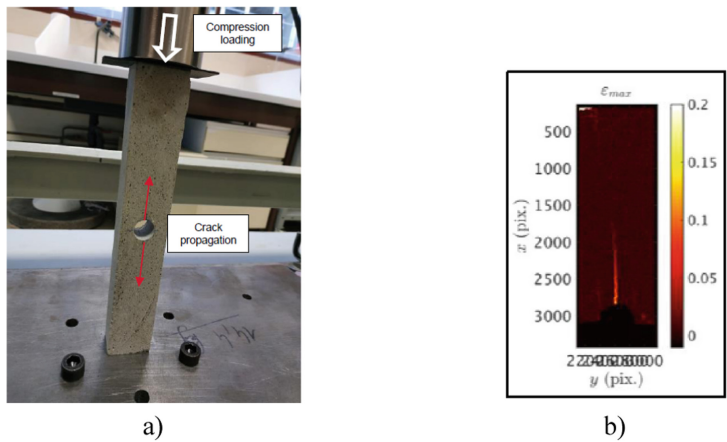


Fig. 4. DCDC test setup, a) and crack propagation measurement system, b).

During the compression test, the measurements from the optical imaging system are being correlated with the load cell measurements of the compression machine. This allows for calculating the interfacial fracture toughness using numerical simulations. Subsequently the correlation with the energy release rate, G_{IC} , can be performed. These calculations were based on the work of [3] from where the Eqs. (1) (2) were deduced.

$$\frac{\sigma(\pi R)^{\frac{1}{2}}}{K_{IC}} = \frac{w}{R} + \left(0.235 \frac{w}{R} - 0.259\right) \frac{a}{R}, \quad (1)$$

$$K_{IC}^2 = \frac{EG_{IC}}{1 - \nu^2}, \quad (2)$$

where:

σ is the global compressive stress

K_{IC} is the interfacial fracture toughness;

R is the hole radius;

$2w$ is the specimen width;

a is the crack length;

E is the E-Modulus;

ν is the Poisson coefficient.

For all the calculations values of $E = 30$ GPa and $\nu = 0.2$ were used.

The results of the DCDC measurements are presented in Table 5 and Fig. 5.

As is clear from Table 5 and Fig. 5 the results of the interfacial fracture toughness measurements are in line with the results of the pull-off tests. In both situations the sample with the low porosity values show similar values for the interface and bulk material indicating homogeneous material. The evolution of the energy release rate (Fig. 5), G , as function of the normalized crack length for the 2 different samples: BH6 and CS6, with a hole centered on the interface clearly show the effect of the different porosity between the samples.

Table 5. Interfacial fracture toughness.

Sample	Toughness K_{IC} (MPa.m ^{0.5})	Crack propagation
BH6 interface	0.69	Interface
BH6 bulk	0.77	Bulk+interface
CS6 interface	0.95	Interface
CS6 bulk	0.92	Bulk+interface

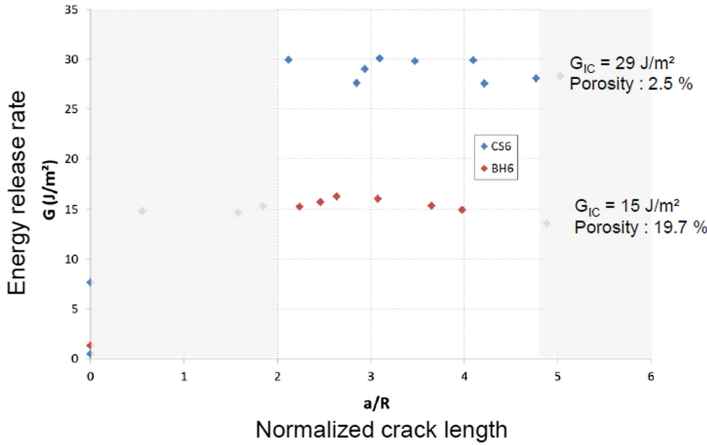


Fig. 5. Energy released rate for different normalized crack lengths; CS6 and BH6 interface test samples.

3.3 Durability

Not only the mechanical properties of the printed material have been determined but also the durability aspects have been studied. These tests were conducted by SGS Intron B.V. [4].

Capillary Water Absorption

The capillary water absorption has been determined on the bulk material (M5) as well as on the surface material (M4) according to NEN-EN 13057. The results are presented in Table 6 and Fig. 6.

The capillary water absorption for the outside layer is approximately 0,1 kg/m² higher than for the bulk material. This can be explained by the fact that the outside layer is rather rough and by the fact that the outside layer has been dried to a larger extent than the bulk layer before start of the test. The water absorption coefficient (indicating the porosity of the material) is identical for the outer layer and the bulk material. The obtained water absorption coefficient is indicative of a very compact material.

Table 6. Water absorption coefficient (S) (kg/(m².h^{1/2})).

Sample/S (kg/(m ² .h ^{1/2}))	M4	M5
A	0.041	0.041
B	0.046	0.046
C	0.042	0.047
Average	0.043	0.045

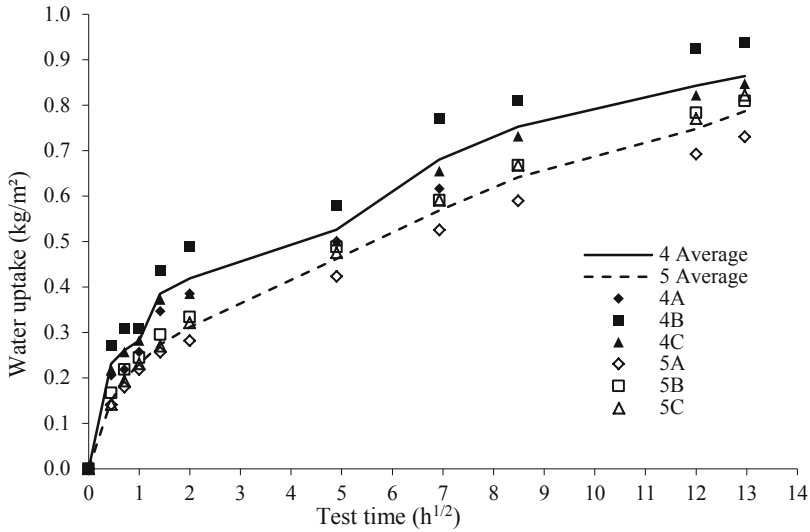


Fig. 6. Capillary water absorption (series 4: surface material; series 5: bulk material)

Frost/Thaw De-Icing Salt Resistance

The frost/thaw de-icing salt resistance has been determined on the surface of a printed object because of the little higher water absorption of this layer and because of its exposition to the external environment. The frost/thaw de-icing salt resistance has been determined with the CDF test conform NVN-CEN/TS 12390-9. The results are given in Table 7.

Table 7. Cumulative mass loss after the CDF test.

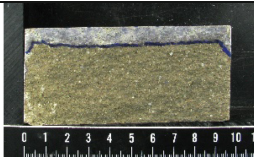
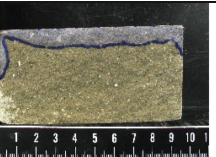
Sample	Absorption (%m/m)	Cumulative mass loss (kg/m ²)	
		After 14 cycles	After 28 cycles
A	0.25	0.032	0.19
B	0.26	0.027	0.11
C	0.18	0.013	0.08
D	0.26	0.022	0.12
E	0.27	0.027	0.17
Average	0.24	0.024	0.13
Std. dev.	0.04	0.010	0.045

The average scaling value is 0,13 kg/m² after 28 cycles. This is approximately one order of magnitude lower than the requirement for pavement blocks and indicative of a frost/thaw de-icing salt resistant concrete.

Chloride Migration Coefficient

The chloride migration coefficient (RCM) on printed bulk material has been determined conform NT Build 492. This coefficient is a measure for the resistance against chloride migration. The testing time is 24 h and the testing potential is 30 V. After testing, the samples have been cleaved and the fresh created surface area has been sprayed with silver nitrate to show the depth of chloride migration into the sample. The results are shown in Table 8. The penetration profiles have a uniform front characteristic of a homogeneous material. The measured chloride migration coefficient of $4 \times 10^{-12} \text{ m}^2/\text{s}$ is a value normally only found for dense blast furnace slag cement containing concrete. Again indicating a very dense material

Table 8. Chloride migration coefficient and profile.

Sample	A	B	C
			
RCM ($10^{-12} \text{ m}^2/\text{s}$)	4.0	3.9	4.0

Microscopic Investigation

A microscopy investigation (fluorescence microscopy) into the quality and the porosity of the interfaces of the printed layers and the surface layer has been conducted. The results are presented in Fig. 7.

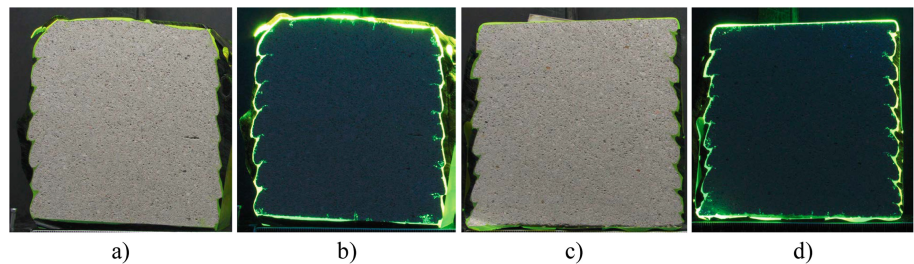


Fig. 7. Microscopic image of the printed object: a) c) daylight; b) d) UV light

The microscopic examination shows that the printed layers in the bulk form a homogeneous material, the original interface between the printed layers is no longer recognizable. The stratification is of course visible on the outside surface. The depth at which the fluorescent resin is visible between the ridges on the outside is approximately 4 to 5 mm. Defects in the outer surface (micro-cracks) are also limited to the outer 5 mm.

4 Conclusions

A 3-D concrete printing technology including a 3-D printer with feedback loops for water dosing and pump yield together with a normal setting OPC based mortar has been developed that is capable of;

- Running smoothly for at least 8 h. with only one operator attending;
- Producing a constant quality of the printed object where;
 - The object is monolithic in behavior even when it comes to adjacent layers;
 - The object is anisotropic (independent of print direction);
- Creating objects that are very dense in structure and hence very durable.

The technology developed and described in this paper will definitely contribute to making the technology of 3-D concrete printing economical viable. For the time being load bearing construction will have to be designed in such a way that in use the construction will always be loaded under compression. The next challenge is to manufacture load bearing structures including some kind of reinforcement.

Acknowledgements. The authors would like to acknowledge the support all of their colleagues for the effort in the realization of the different tests. The support of the teams at the TU/e and SGR Paris in performing some of the tests is gratefully acknowledged.

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Design and Fabrication of a Non-standard, Structural Concrete Column Using Eggshell: Ultra-Thin, 3D Printed Formwork

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Abstract. This paper describes the design and fabrication process of a concrete column cast in ultra-thin, 3D printed formwork, using a process known as Eggshell. The column was prefabricated as part of a real-world construction project, serving as the main load-bearing element for a reciprocal timber frame structure. The fabrication of the column required upscaling of the Eggshell process, to allow for the fabrication of elements of an architectural scale. Furthermore, several challenges had to be addressed such as: integration of reinforcement, establishing the formwork design space, and scaling up the 3D printing process. For the production of the final column a 1.5 mm thin formwork was 3D printed, after which it was combined with a prefabricated reinforcement cage and filled with concrete in a set-on-demand casting process. The successful realization of the project provides a first example of a full-scale building element produced with the Eggshell fabrication process. By 3D printing the formwork, geometrical freedom in concrete construction is greatly expanded, as well as formwork waste reduced.

Keywords: 3D printing · Formwork · Digital concrete · Robotic fabrication · Set-on-demand concrete · Reinforcement

1 Introduction

Formwork is an essential element in construction of concrete building components, holding freshly poured concrete in place until it reaches its final, hardened shape. The shape of the formwork ultimately determines the geometry of the concrete and this is – along with material properties and reinforcement – what determines structural performance. Research shows that by optimizing concrete geometry, it is possible to achieve material savings of up to 70% compared to a standard concrete building component [1]. These types of optimized building components, however, are expensive to fabricate,

mainly due to the difficulty of constructing the formwork [2]. This is one of the reasons complex, non-standard concrete structures remain uncommon. However, with cement production being responsible for 8% of global anthropogenic CO₂ emissions [3] it is imperative that material-efficiency is considered a key driver in the construction process. In order to make concrete construction sustainable, more efficient ways of formwork fabrication therefore have to be developed.

Digital fabrication presents a potential solution for this problem and various innovative formwork fabrication processes have been developed. Subtractive processes such as computer numerically controlled (CNC) milling of wood [4], foam [5], ice [6] and wax [7] enable precision-manufactured formwork, however, they are often wasteful and time-consuming. Adaptive processes such as Smart Dynamic Casting [8] (SDC) or flexible mould techniques [9, 10] produce no waste but instead impose limitations in the type of geometry that can be produced [11].

Lastly, additive manufacturing processes offer a relatively wide range of geometric possibilities. Binder jetting [12] especially has high geometric flexibility, although the formwork material cannot be recycled, making it a resource-intensive process. Fused deposition modelling (FDM) 3D printing offers potential for formwork recycling as well as geometric freedom. However, FDM produces fragile structures that need some form of support to resist the hydrostatic pressure exerted by the fresh concrete. This can be done using counter pressure casting [13] or a printed external scaffolding [14]. Counter pressure casting, however, increases complexity when casting and an external printed scaffolding greatly increases printing time.

In contrast to these approaches is the fabrication method Eggshell [15], the subject of this paper. Eggshell enables the use of FDM 3D printing of ultra-thin formworks with a high degree of complexity, good surface quality and no additional support. The key enabler of this fabrication process is a set-on-demand Digital Casting (DC) approach, first developed during the SDC project. DC allows for controlled hydration of the concrete, resulting in only a limited amount of lateral pressure exerted on to the formwork.

This paper describes the challenges that emerged in the design and fabrication process of a non-standard, structural, full-scale concrete column using Eggshell. Eggshell presents a novel fabrication system, which until recently had only been explored for the fabrication of smaller scale elements with a high degree of complexity. Thus, the main challenge lies in scaling up the process for the fabrication of full-scale building components. The first step of bringing this technology into an architectural scale was done with the project: Future Tree, built for the Swiss engineering firm Basler & Hofmann [16, 17].

2 Fabrication Concept and Setup

2.1 Fabrication Concept: Consecutive Fabrication

The Eggshell fabrication process leverages on a fast setting set-on-demand concrete that is digitally cast into an ultra-thin, 3D printed formwork. The process aims to 3D print the formwork and cast concrete *simultaneously*, enabling the production of highly

complex structures. This concept has been successfully demonstrated with prototypes up to 1.60 m tall [18]. However, scaling this process up to a building scale introduced two major challenges: slow printing speed in comparison to the filling rate of the fast-setting concrete and the inclusion of reinforcement compliant to building codes. The experiments presented in this paper, therefore, make use of a *consecutive* fabrication process as illustrated in Fig. 1. In this process a formwork is 3D printed (1) after which it is combined with a reinforcement cage (2) and filled with a set-on-demand concrete (3). One advantage of this process is that the filling rate (vertical speed at which concrete is cast) does not have to be synchronized with the printing rate (vertical speed at which the formwork is printed), see Fig. 2b.

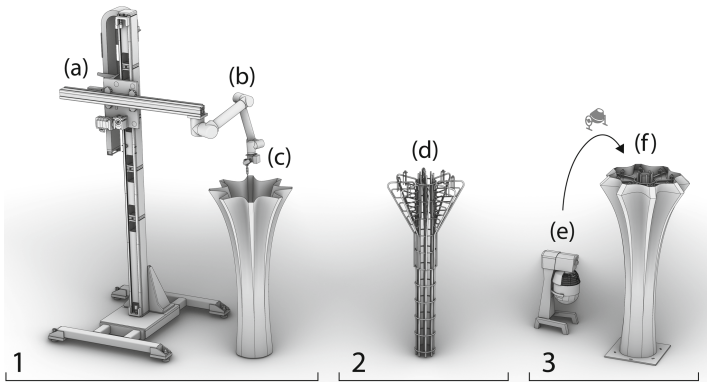


Fig. 1. The consecutive fabrication process and setup.

However, consecutive fabrication is only suitable for the production of elements with a relatively simple geometry, because of two major limitations:

1. As concrete has to be fed in from the top, the bottom of the formwork has to be accessible for casting. If the bottom is not accessible, cast concrete will deposit on the walls of the formwork, causing uneven hydration, poor surface quality, cold joints and possible blockage (see Fig. 2b).
2. A prefabricated reinforcement cage cannot always be fitted inside of the formwork, especially in the case of a complex formwork with high curvature (see Sect. 3.1).

2.2 Fabrication Setup

The fabrication setup (Fig. 1) consists of a Universal Robots UR10 six-axis robotic arm (b) mounted to a Siemens vertical linear axis (a). Attached to the robotic arm is a custom-made filament extruder (c), which uses 2.85 mm Polyethylene Terephthalate Glycol (PET-G) filament and has a maximum flow rate of 0.35 kg/h. The total build volume of the setup is $1.2 \times 1.2 \times 3.6 \text{ m}^3$ (width, length, height).

The material mix and acceleration system are inherited from the SDC project [19]. In the process a large batch of concrete is prepared with a retarder, ensuring its workability

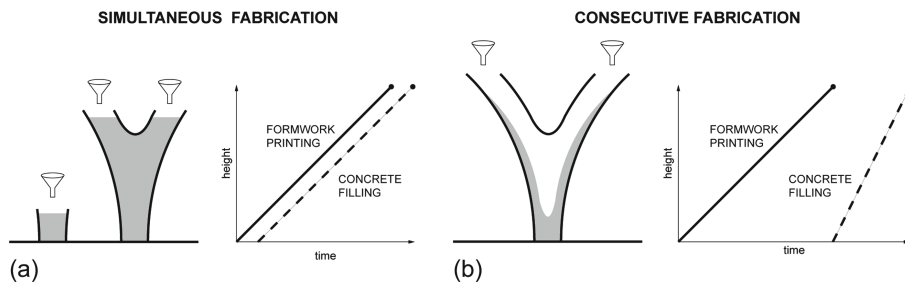


Fig. 2. (a) Simultaneous fabrication process, the graph shows the fabrication height (y-axis) over time (x-axis). As the slope of the two graphs of printing and casting is the same, the printing rate is equal to the filling rate (b) Consecutive fabrication process: Slope of concrete filling is higher than the formwork printing process, meaning a faster filling rate than printing rate.

for up to eight hours. Smaller batches of concrete are then taken and mixed with an accelerator in a planetary mixer (e), after which the accelerated batches are cast into the formwork (f). The main mix design has been slightly adapted from [19] in order to include polypropylene fibres. The W/B ratio was kept the same but the proportion of admixtures was slightly adapted to accommodate the change of rheology brought by the fibres, and the fact that the concrete needed less retardation time. This led to increase the superplasticizer content but decrease the sucrose content. The accelerator content was also restricted, for durability concerns, to the amount advised by the manufacturer of 4 wt% per cement content. Several slightly different material mixes were used throughout the development phase (Sect. 4.2), some including aggregates up to 8 mm and some with aggregates up to 4 mm (such as the final mix design used). Several of the material mixes used therefore technically classify as a mortar but for the sake of simplicity, all are referred to as a concrete.

3 Challenges

3.1 Integration of Reinforcement

The Future Tree column is a structural building element onto which a reciprocal timber frame of 100 m² is placed [16]. This results in a pavilion situated in an outside courtyard on the premises of Basler & Hofmann in Esslingen, Switzerland. Due to public access to the pavilion the structure had to ensure building code compliance. Therefore, despite the fact that several novel reinforcement concepts exist for the Eggshell process (active reinforcement, steel hooked fibres [15]) it was chosen to use conventional, passive reinforcement. A benefit of the Eggshell fabrication process is that it allows for the relatively easy integration of such reinforcement: a reinforcement cage can be prefabricated and installed inside the thin formwork. Still, it is not possible to combine every reinforcement cage with its formwork, especially as geometric

complexity increases (Fig. 3a). Splitting the reinforcement into several parts could provide a solution, however at a cost of fabrication tolerance. The design of the column was therefore adapted to allow a single reinforcement cage to be placed in from the top (Fig. 3b).

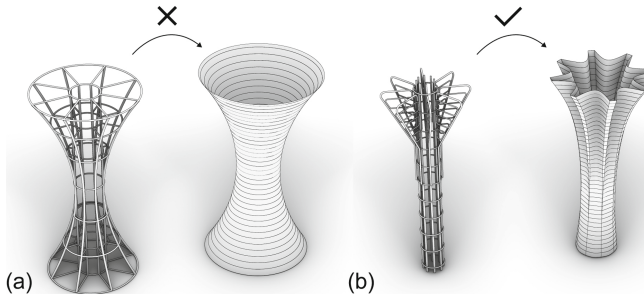


Fig. 3. (a) A combination of reinforcement and formwork geometry that cannot be combined. (b) Reinforcement can be placed inside the formwork from top.

The reinforcement cage was designed to closely follow the column geometry. The reinforcement in the core of the column was dimensioned to resist the global loads of the timber roof, while minimum reinforcement was disposed in each of the column's eight ribs. A small concrete cover (28 mm) results in the ribs since they are very thin (70 mm at the thinnest point). Therefore, the reinforcement had to be fabricated to a tolerance of 10 mm – which proved to be very challenging for the manufacturer – and stainless reinforcing steel was used to avoid corrosion issues. The maximum concrete cover was set to be within limits of international building code recommendations.

3.2 Formwork Design Space

This section discusses two sets of experiments: (1) maximum overhang that can be fabricated with Eggshell and (2) effect of formwork geometry on the concrete casting process. These experiments were necessary in order to determine the final geometry of the Future Tree column.

Materials and Methods. In both experiments, 3D printed formworks were filled with the set-on-demand concrete (Sect. 2.2) to observe the point of breakage. Relevant parameters are the geometry of the formworks, as well as the filling rate (vertical casting rate in mm/min) and the 'setting time' (considered here as the time in minutes after which the concrete can sustain its own weight and is therefore not exerting lateral pressure onto the formwork under our normal operation conditions). This time roughly corresponds to the onset of the acceleration period. The maximum pressure can be calculated using the equation for hydrostatic pressure Eq. (1).

$$P = \rho \times g \times h \quad (1)$$

Within each set of experiments, the vertical filling rate and setting time are the same, and therefore so is the evolution of the hydrostatic pressure acting on the formwork. However, as geometry and surface to volume ratio of the formwork changes, breakage behaviour most likely also changes.

Experiment 1: Overhang. Four formworks were 3D printed with an overhang of 15°, 25°, 35° and 45°. Through penetrometer measurements [20] it was determined that setting time was 50 min after acceleration and casing. Assuming a filling rate of 2 mm/min this gives a maximum of 100 mm of concrete that is exerting pressure on the formwork. Filling in the values in Eq. (1) for a material density of 2300 kg/m³, acceleration of gravity of 9.81 m/s² and height of 0.1 m gives a maximum pressure of 2.26 kN/m². The results of the first experiment (Fig. 4a) show that the formworks with an overhang of 15 - 35° could be fabricated successfully, however, the 45° formwork failed after 50 min of casting, equalling to a pressure of 2.26 kN/m².

Experiment 2: Geometry. Secondly, breakage behaviour was studied for formworks with a different cross-section. Two design options, one with a circular shape and another octagonal with convex edges were 3D printed in a 1:1 scale (Fig. 4b). It was expected the formworks could sustain a filling rate of 5 mm/min. Two iterations of the experiment were completed. Both iterations showed that the circular formwork was able to be fully filled with concrete, whereas the octagonal formwork broke at 290 mm of concrete height in the first test and 300 mm in the second. This gives an average breaking height of 295 mm, equalling to 6.66 kN/m² using Eq. (1). In both cases breakage occurred in one of the ribs, with a vertical crack starting at the bottom of the formwork.

Conclusion. These tests are only a first insight into the design space of Eggshell, meant to provide some guidelines for the Future Tree design. Indeed, the results are not conclusive and further work will focus on systematic tests to fully quantify the limitations of the system, as breakage behaviour is not yet understood well. However, some design guidelines could be determined:

1. Experiment 1 showed that an overhang of 35° could be fabricated without problems and this was therefore set as the maximum design angle.
2. Experiment 2 showed that the circular formwork was able to sustain a higher amount of pressure and could therefore be filled using a faster filling rate. As one of the aims was to reduce the total casting time, it was therefore decided to adjust the design to the circular cross-section in the bottom.

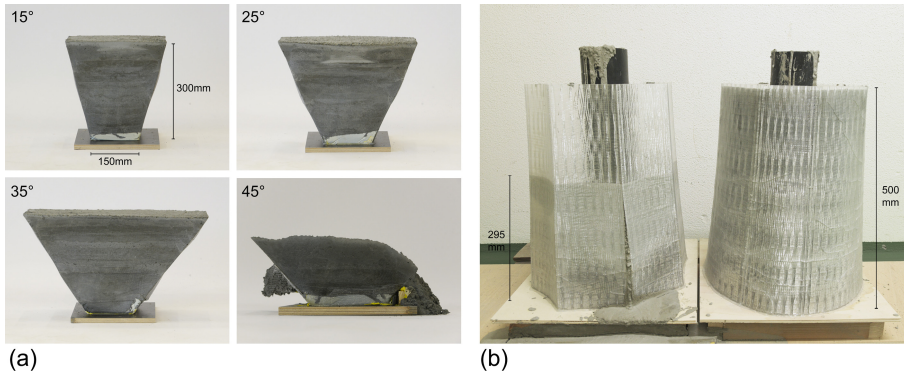


Fig. 4. (a) Overhang experiments, showing breakage in the 45° model. (b) Geometry tests, breakage occurred in the polygonal shaped formwork (left) whereas no breakage occurred in the circular shaped formwork (right).

3.3 Large Scale 3D Printing

Due to the relatively large dimensions of the column (a top diameter of 1 m) it proved challenging to 3D print the thin formwork. For prints with a diameter exceeding 0.7 m, severe issues of layer delamination were found. These issues can be explained by deformations due to shrinkage of the printed material, a common problem in 3D printing [21]. Shrinkage was further amplified as the Eggshell print setup is situated in a large hall with sub-optimal printing conditions (low ambient temperature). A solution could be a heated chamber around the printing setup, however, this was deemed unfeasible due to the large dimensions of the setup. Alternatively, a series of experiments was conducted, aiming to define the threshold of when delamination would occur. Several sets of experiments were conducted in which a circle of 1 m in diameter was printed up to a height of 50 mm with a constant speed of 45 mm/s [15]. The only changing variable in between tests was a zigzag pattern that was applied to the geometry. By dividing the circular geometry into points and shifting these points in- and outwards, a series of concave polygons was created. The experiments allowed to conclude that layer delamination could be prevented by limiting the length of a straight edge to a maximum of 70 mm. This fabrication- and material constraint was turned into a design parameter, that was used to design the final formwork texture (Fig. 7b).

4 Design and Fabrication

4.1 Design

As the column had to support the timber roof structure the starting point of the design was the eight timber beams at the bottom of the roof. The timber beams connect to the column through eight vertical ‘ribs’. Between these ribs, material was removed in order to reduce the amount of concrete used in the column.

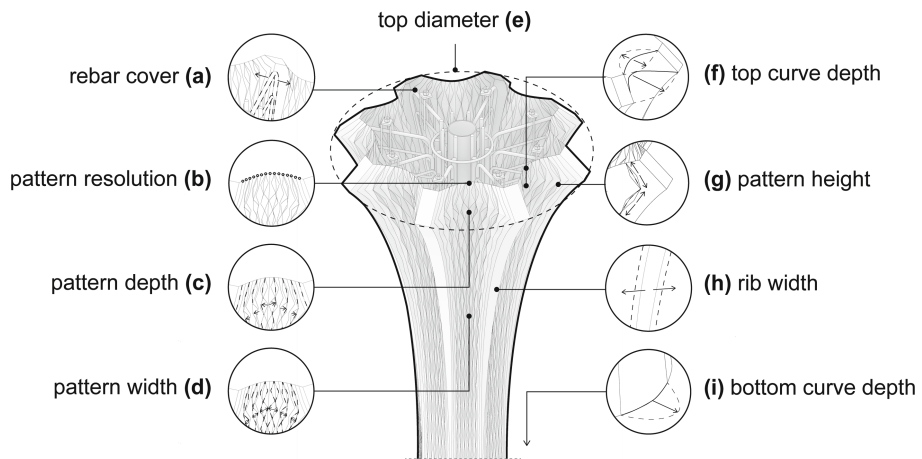


Fig. 5. Design parameters.

The column was designed using McNeel Rhinoceros 3D, Grasshopper 3D, as well as through custom Python scripts. A parametric model (Fig. 5) was generated that allowed for easy manipulation of the column design. The design could be changed based on the results of the experiments conducted such as: overhang (Fig. 5e), pattern geometry (Fig. 5b, c, d, g), shape of the cross-section (Fig. 5f, j) and reinforcement cover distance (Fig. 5a). This allowed for constant modification of the design based on new findings. Finally, the parametric model could also be used to directly generate the fabrication data, eliminating the need of an additional step of slicing the geometry.

4.2 Fabrication

In order to determine the constraints of the full Eggshell process in a large scale, it was necessary to conduct a series of 1:1 experiments. Three full-scale column prototypes were therefore fabricated and with each prototype, different improvements were made, as well as new problems encountered (Table 1). A material mix with aggregates up to 8 mm was used for Prototype 1 and 2, whereas for Prototype 3 and 4 a material mix with aggregates up to 4 mm was used.

Table 1. Overview of problems and improvements in the different prototypes.

Prototype	Improvements made	Problems encountered
#1 (Fig. 6a)	–	- Unpredictable concrete behaviour due to changing ambient conditions.
#2 (Fig. 6b)	- Material testing during fabrication (flow diameter and penetrometer).	- Reinforcement not made to tolerance (Sect. 3.1).
#3 (not shown)	- Reinforcement bent using template.	- Geometry of bottom failure (Sect. 3.2).
#4 (Fig. 6e)	- Geometry changed.	–

After the knowledge gained from the three prototypes, the fourth and final prototype (Fig. 6e) could successfully be fabricated. The formwork (Fig. 6c) was printed in a fully autonomous, continuous process with a layer height of 1 mm, layer width of 1.5 mm and printing speed of 45 mm/s. Total printing time of the column formwork was 26 h with a toolpath length of just over 4 km.

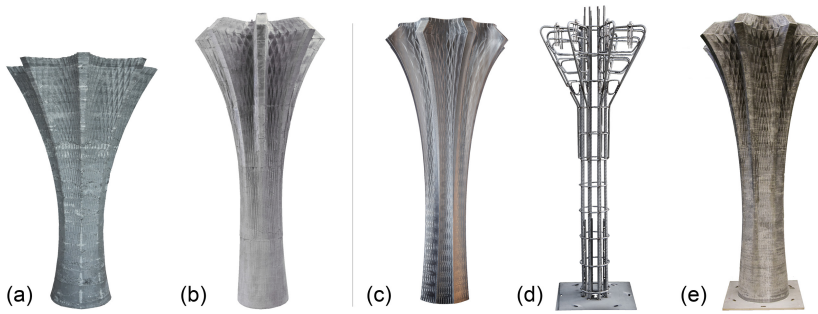


Fig. 6. (a) Prot. #1. (b) Prot. #2. (c) Formwork. (d) Rebar cage and bottom plate. (e) Final column.

The reinforcement (Fig. 6d) was then lifted in and the formwork precisely aligned with the steel base plate using a laser cut wooden template. Eight vertical reinforcement bars with a length of 600 mm had been pre-welded to the base plate, hereby ensuring a proper connection between concrete column and base plate by fully encasing the vertical bars. An additional laser cut wooden plate was placed around the column at a height of 2 m, in order to ensure deviation at the connection point would not exceed 5 mm. Subsequently the formwork was filled with the set-on-demand concrete over a period of eight hours. Total volume of the column was 270 L and the filling rate was varied over the height, starting with a high filling rate (6 mm/min) at the bottom and resulting in a lower filling rate (2 mm/min) at the top of the column. Filling rate at the top of the column had to be lower for two reasons: 1) higher overhang resulting in weaker bond between printed layers, 2) the larger size meant a lower surface to volume ratio, resulting in higher stresses on the formwork. After casting, the column was covered and left to cure for 14 days. The formwork was then removed by making a vertical seam with a heat-gun and stripping the column using pliers. Finally, the column was transported to site and connected with the foundation. The timber roof was then added on top of the column in five prefabricated modules.

5 Discussion and Conclusion

The successful fabrication of the column as presented in this paper is a milestone for this research, bringing it from a prototype in a laboratory to a full-scale, structural building component. It shows that FDM 3D printing of formwork in combination with digital casting is a viable strategy for fabricating architectural-scale components. The

final formwork for the column weighed just 8 kg, around one hundredth of the weight of the finished concrete column including reinforcement. There are however several key aspects in which further research is necessary:

- 1) It proved very challenging to integrate the reinforcement cage with the necessary tolerance. Although the 3D printed formwork can be manufactured to millimetre-tolerance, current reinforcement techniques are still unable to produce complex reinforcement with high precision.
- 2) The aim of the Eggshell research project is to fabricate complex concrete structures in a *simultaneous* process of printing and casting. For this to be viable for large-scale fabrication, current 3D printing tools have to be improved to allow for higher output and ultimately, faster printing.
- 3) Utilizing 3D printed formwork has the potential to be a fully circular process, as removed formwork can be cleaned, shredded and extruded into new material. This, however, has not been verified but is currently under investigation.
- 4) The processes concerning stresses in the formwork as a result of concrete hydrostatic pressure are not yet fully understood for non-standard shapes so that more work is required on this front, both theoretical and experimental.
- 5) Although design efforts were made to reduce concrete in the column, no sophisticated optimisation processes were used. There is however great potential for such methods and this will be further explored in future work.



Fig. 7. a) Column placed on site (Image: Basler & Hofmann AG, Stefan Kubli). b) Close-up of top.

Acknowledgements. The authors would like to express their gratitude to the following people: Bruno de Pinto Aranda for his continuous support in material development and fabrication. Heinz Richner, Andreas Reusser, Phillippe Fleischmann and Michael Lyrenmann for their technical support. Ania Apolinarska for her work as a project leader in the Future Tree project. Sara Mantellato, Timothy Wangler and Lex Reiter for their input on the material and Gonzalo Casas and Romana Rust for their assistance regarding robotic fabrication. Lastly, the Swiss National Science Foundation (NCCR Digital Fabrication agreement number 51NF40-141853) for supporting this work.

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Complex Architecture in Printed Concrete: The Case of the Innsbruck University 350th Anniversary Pavilion COHESION

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Abstract. During the summer semester 2018–2019, a 3D concrete printed (3DCP) pavilion consisting of 47 unique free form parts was realized in the central square of the engineering campus of the University of Innsbruck. In a period of just 11 weeks, it was designed, engineered, manufactured, and assembled on-site to provide an attractive meeting space for students and staff alike. The parts were printed off-site in an extrusion layering process, using variable print speeds and filament heights to obtain radially fitting segments that were transported to the building site. A selection of parts was reinforced with innovative woven carbon fiber reinforced polymer (CFRP) strands, while the others were reinforced with in-laid conventional reinforcement bars. The parts were bolted to an on-site cast fibre-reinforced concrete floor and the seams were sealed with a silicone adhesive. This paper presents the entire project, including architectural considerations, geometrical parametric modelling, structural (safety) principles and design, manufacturing, and construction, including connections.

Keywords: 3D concrete printing · Project · Complex geometry · Reinforcement · CFRP

1 Introduction

Extrusion-based 3D Concrete Printing (3DCP) is increasingly finding its way into actual built projects in the public domain. Menna et al. [1] provide an extensive list of recent projects. The quest is on to actually realize the promised potential of the technology, such as reduced use of material, geometrical freedom, and high speed of construction. In 2019, the COHESION pavilion was designed and erected to showcase the State-of-the-Art of 3DCP. The project was part of the celebrations of the 350th anniversary of the University of Innsbruck, and featured a complex, irregular, segmented, doubly curved and robotically 3D printed concrete shell, which was constructed in a public square on the Campus Technik site (Fig. 1).

The application of 3DCP in projects brings the need for customized approaches, in design, structural engineering, production, and construction, in order to allow the

benefits to be reaped while also meeting the specific requirements the technology sets in terms of manufacturing possibilities. Considering the novelty of 3DCP and the limited experience in professional practice (a rare exception given by Salet et al. [2]), this paper gives a detailed description of the COHESION pavilion project, to highlight the specifics of applying 3DCP technology in the built environment.



Fig. 1. Innsbruck University 350th anniversary pavilion COHESION, 2019 (Photo: Rupert Asanger).

2 Architectural Design

Initial sketches and preliminary studies had been developed by architecture and technical sciences students already during the summer term of 2018. It featured a circular geometry completely filling one of the water basins that characterize the square linking the various buildings of the Technik Campus in the western part of Innsbruck. Besides setting up a parametric model for studying and experimenting the overall shape, the possibilities of woven Carbon Fibre Reinforced Polymer (CFRP) strands as a reinforcement method for 3DCP were explored.

While keeping the idea of building a pavilion on the campus site, the design had to be altered to fit both the regulations of the construction site and the printing requirements. Due to budget and time constraints the footprint of the pavilion was reduced to cover a third of the initial proposal, shifting the design from covering the entire volume of the water basin to a free-standing pavilion (Fig. 3). The outer diameter was approximately 6 m, while the maximum height was some 2.6 m. Implementing the possibilities of 3DCP and creating a complex freeform was guiding the design process to combine both convex and concave surfaces showing the potentials of the technology. Although the 3DCP technology allows a wealth of geometrical options, it should

be realized that these do not provide absolute freedom of form or size. At a very early stage in the design process, a principle strategy had to be chosen to match the manufacturing possibilities with the architectural design. It was decided to cut the overall geometry into radial segments that could be produced off-site. The vertical section of a segment (i.e. the radial plane) was to correspond with the (horizontal) u,v-plane during printing. In other words, the printed parts were rotated 90° after printing. This strategy allowed a great freedom in the design of the outer face of the object, and a flexible segmentation to meet production, transportation, and assembly needs (i.e. a segmentation that could be adjusted during the design process without interfering with the overall design result). To avoid disruption of the printing operations in the short time frame, as well as for structural reasons, a continuous print path (no start-stop actions) without openings was applied. The design/manufacturing strategies were characterizing for the appearance and used as an architectural tool to differentiate the pavilion from other 3DCP projects.

A simple parametric design model permitted to implement architectural requirements and to examine several constraints of 3D concrete printing processes, such as geometry, topology, weight, transport and assembly (Fig. 2). This led to faster modifications within the design process and allowed controlling double-curved surfaces on predefined local areas. Adapting to an uneven segmentation of the pavilion resulted in an improved distribution of weight between the individual parts certainly improving processes further down the line such as transporting and assembling.

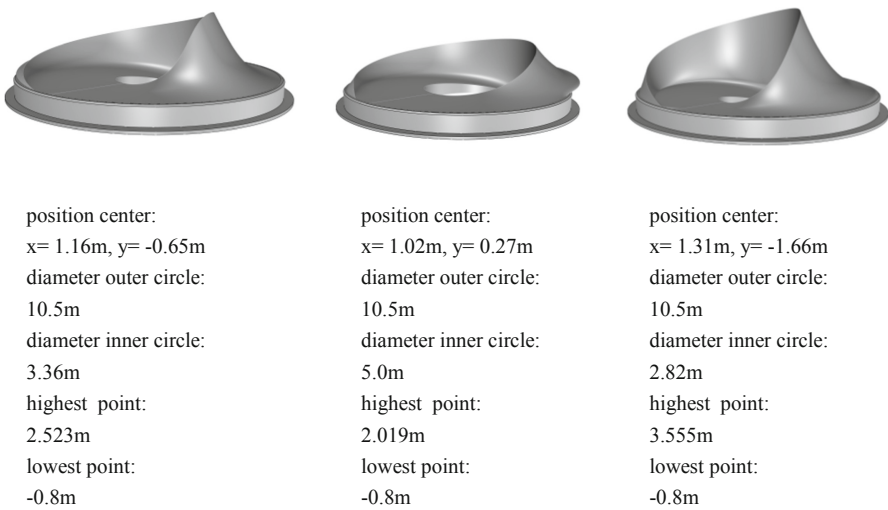


Fig. 2. Parametric Design Study in the initial phase; guiding curves and sections are link and controlled via graphical interfaces and give a live feedback to assist design decisions.

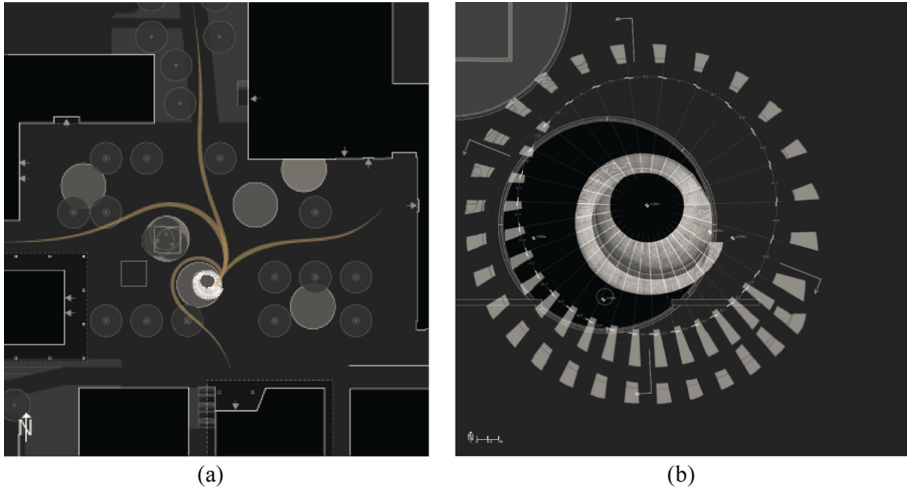


Fig. 3. (a) Location of the Pavilion in the main courtyard at the Campus; (b) Segmentation into 47 parts

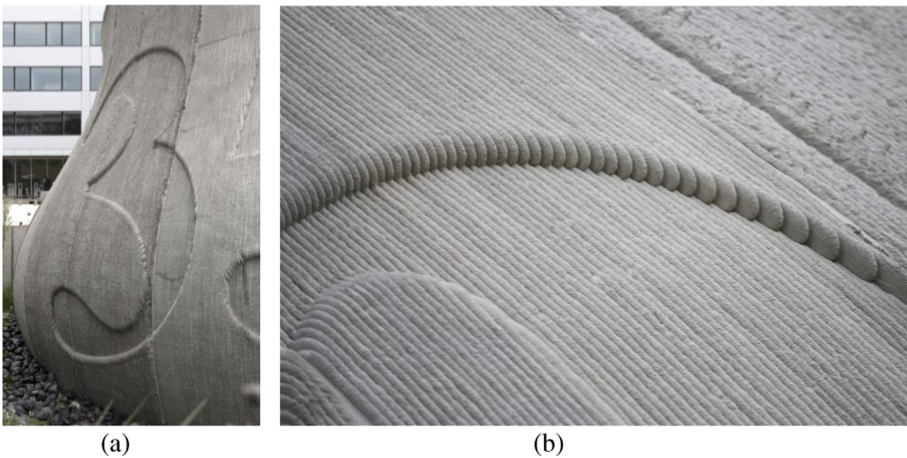


Fig. 4. (a) Close-up of the embossed '3', (b) close-up of the '0' (Photo: Rupert Asanger).

For the final design proposal the existing central water retention basin of the main courtyard at the Campus Technik had been chosen due to its prominent location.

The designed structure rises westwards (up to 2.70 m) towards the main wind direction, a small 'bar table' cantilevers out and from the east-facing access a slightly declining ramp leads to the interior, where integrated seating invites to linger and to relax. On the outer shell, the numbers 3-5-0 are embossed in font size 2 m to clearly mark the University's anniversary (Fig. 4a, b). The whole object resulted finally in a diameter of 6.20 m, a foot print of approx. 22 m², a surface area of 88 m². It was

divided into 29 unequal radial sections, ranging from 8.91° to 16.79° . Over a total of 18 of those sections, the parts were also tangentially divided into two rings. This resulted in a total of 47 parts (Fig. 3b).

3 Structural Design

Due to the short time span of three months from initial design to realization, 3D printing was the ideal manufacturing method for the project. Also, the uniqueness of each of the 47 parts of the structure has generated obvious challenges for the structural design. Considering the shear novelty of technology and the short time span available, a robust and efficient approach was opted for. The structural principles were first determined:

- each part was designed to be self-supporting and not rely on structural interaction with other parts,
- extensive reinforcement had to be avoided as its placement would have disrupted the printing process,
- with one noticeable exception of the heavily cantilevering ‘bar table’, the parts were dimensioned so as not to exceed the concrete tensile strength.

Reinforcement was only applied to ensure structural safety – not to act in tension in in-service conditions, as is common in conventional concrete structures. Due to the orientation of the print filament, the tensile stresses act parallel to the print filament axis, thus avoiding dependency on the uncertain tensile strength of the interfaces between the filaments.

To determine the loads, the pavilion was considered as a CC1, RC1 type structure as defined by the EN 1990-1, with a 5 year reference life time. As a result, the partial load factors may be reduced by a factor $K_{FI} = 0.9$. The distributed and concentrated vertical loads were taken from use category A (balconies), with $q_k = 2.5 \text{ kN/m}^2$ (recommended value) and $Q_k = 3.0 \text{ kN}$ (upper boundary value) considered to act on all surfaces with a slope of 45° or less with the horizontal. Meanwhile, the concentrated horizontal line and vertical point loads were taken from use category C5, i.e. $q_k = 3 \text{ kN/m}$ acting at a height of 1.2 m. In addition, an additional horizontal (characteristic) pulling load of 0.8 kN distributed over 500 mm was considered to act in either direction at the top of the standing elements (Innsbruck is full of climbers, after all!). In all parts, the concentrated loads were governing in the dimensioning.

Each part was individually designed and analyzed. A 2D Finite Element Modelling (FEM) approach in one or more radial planes of the part was adopted, using DIANA© software. Although ignoring beneficial effects of the tangential curvature, this method was chosen due to its modelling and analysis efficiency and conservative nature. The smaller parts were modelled with surface geometries directly, while for the larger parts initially a model with linear geometries was used to gain insight in the order of magnitude of stresses and develop a principle design of the infill pattern, which was followed by a surface geometry-based analysis to check and verify. For the characteristic flexural tensile strength $f_{ct,flex,k} = 5.9 \text{ N/mm}^2$ was used, which was lowest value of experimentally obtained flexural strength data. A material safety factor of $\gamma_M = 2.0$

(rather than 1.5, as common for concrete) was applied to account for the limited amount of experimental data available.

The structural geometry design was based on the assumption that any geometrical width should be a multitude of the print filament width of 3 cm. Efficient material use requires the application of internal structures. These were mostly designed in an orthogonal manner (vertical and horizontal) as it was expected this would be the easiest to control in printing and would result in parts that are less susceptible to shrinkage stresses due to uneven drying than parts with a lattice type infill (diagonals).

Care was taken that the structural dimensioning matched the requirements of a continuous print path in each layer as well as a consistent print path topology over the print element height. Regardless of the structural analysis results, the bottom side of the high standing elements was designed to be at least 4 print filaments thick (12 cm), to improve the element stability (both in in-service conditions and during hoisting in the construction phase) and provide 'body' for drilled anchor connections to the fiber reinforced concrete foundation slab.

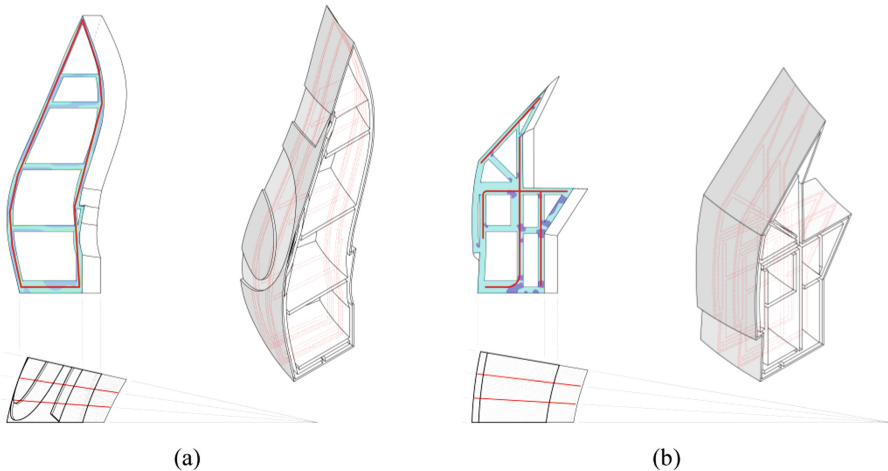


Fig. 5. (a) Part 8a - CFRP reinforced; (b) Part 17a – conventionally reinforced with 6 mm bars. In both figures, the position of the reinforcement is indicated with red lines.

An innovative reinforcement concept of woven CFRP strands was applied during the project. Due to time constraints, this innovation was only applied to a selection of the higher parts in the outer ring, while manually embedded $d = 6$ mm conventional reinforcement bars were applied to reinforce critical sections of the other parts (Fig. 5a, b). As advanced bar bending equipment was unavailable at the manufacturer, only straight bars or bars with 190° angle were used. In several cases, the infill pattern was particularly designed to allow embedment of such bars.

For instance, elements 21–23 have a near vertical inner support in which the steel bars were embedded, to provide a continuous vertical reinforcement that could not be achieved in the curved outer surfaces of the part.

The CFRP strands have been woven around a pattern of pins according to the outline of each element. In some cases, additional CFRP elements were produced to be embedded in the inner structure. All CFRP elements form continuous (semi-rectangular) geometries so that their reinforcing performance would not depend on the bond with the concrete, as this should be expected to be limited due to the strand smoothness. For each CFRP element, a double strand was woven, resulting in a design tensile strength of $F_d = 2 \cdot A_{\text{tex}} \cdot f_{d,\text{tex}} = 6.5 \text{ kN}$. Generally, reinforcement (either CFRP or steel) is applied twice in each part, between layers at approximately $1/5^{\text{th}}$ and $3/5^{\text{th}}$ of the part height, and calculated to be sufficient to carry the ultimate limit state tensile loads in the respective section.



Fig. 6. The cantilevering ‘bar table’ part during construction. This part was the only part that required temporary support during construction. The radial face is filled with cast mortar to increase in-plane moment resistance and stiffness. The footing is enlarged to go under its inner tangential counterpart, for overall stability.

A small number of the parts of the outer ring would not have been stable on themselves if the tangential division would have been vertical. Rather, an enlarged footing was designed for these parts that was hidden from sight by the inner tangential parts that reach out over them. Figure 6 clarifies this. This figure also shows the ‘bar table’ part. It is the only part that relies on steel reinforcement bars to take tensile loads in normal in-use situations. These bars are placed each 10 layers of filament. In addition, one radial face is filled with cast mortar to increase in-plane moment resistance and stiffness (Fig. 6). The cast mortar was applied directly after printing, when the part was still in its horizontal position.

4 Parts Manufacturing

The COHESION pavilion went through a design phase where all issues of logistics, assembly, structural design and spatial expression had been part of the manufacturing decisions. Within less than two weeks, 47 parts with an average path length of 760 m accumulating to a total of 36 km had to be printed. At an average nozzle speed of 300 mm/s, this results in a net printing time of 33 h and 20 min. All elements combined a weight of 12.2 tons while covering a built volume of 23.3 m³ which resulted in an average density of 520 kg/m³.

For the print path development of each part, the challenge was that every layer has a non-uniform thickness, due to the wedged shape of the parts. This translates into a wedge for each layer too, that is dependent on the part geometry – particularly the distance of each point in a layer to the radial center point. As a result, the minimum layer thickness is only 4.5 mm, while the maximum width is 12.0 mm. In the print path generation, this can be solved relatively easily by introducing non-parallel slicing planes. However, processing of the material through an extruder with constant material output (i.e. a constant pump rate) necessitates the control of the robotic movement speed according to the required amount of material at each point of a layer. Doing so, the alignment of the extruder in reference to the slicing planes is also essential for a high quality print and beyond that, this takes full advantage of the 6° of freedom industrial robots offer.

3D printing was undertaken at the facilities of Incremental3d, a spin-off of the University of Innsbruck, using an ABB 6640 industrial robot with working radius of 3.2 m. Industry partner Baunit supported the project with the “Bauminator®”, a harmonized 3DCP system containing mortar, catalyst and a printing nozzle of 10 mm in diameter (Fig. 7). The injection of the catalyst happens at the head of the nozzle and the so called “activated” mortar obtains its required consistency for printing. Table 1 lists some properties of the applied print mortar, Bauminator® PrintCrete 230.



Fig. 7. Printing of Part 22a with the Bauminator system. Layers constantly change in height, between 4.50 mm and 12.00 mm.

Table 1. Bauminator ® PrintCrete 230 properties.

Property	Value	Code
Maximum aggregate size	2.0 mm	–
Dry bulk density	1,850 kg/m ³	–
Flexural strength, approximately	8 MPa	EN 196-1
Compressive strength, approximately	25 MPa	EN 196-1

The parts were printed on timber board materials, which were in turn fixed onto standard pallets that could be moved by fork lift trucks. The parts were covered in plastic foil after printing to avoid dehydration. Due to the strict opening deadline and transportation planning, several parts had to be moved to site after less than a week of curing.

5 On-Site Construction

The transportation of over 250 km of the concrete parts from the prefab location to the site was carried out by a conventional 40t truck for international freight traffic, in three transports. This method avoided deadhead running and high transportation costs. After arrival the parts were collected next to the construction site.

In the water basin on site, after removing the top layer of soil, a fibre reinforced concrete (FRC) base plate had been poured to obtain a stable and level foundation for further construction works. To erect the pavilion each concrete part needed to be turned carefully by 90°. Using slings through the open inner structure of the parts (Fig. 8), instead of sealed anchors, allowed adjusting easy the center of gravity and avoided visible impact on the outer shell.

Correctly positioning the parts posed the next challenge. The overall geometry itself does not provide a clear point of reference, but neither do the individual parts. To minimize the risk of cumulative inaccuracies resulting in parts that do not fit the assembly sequence was started from where part number 29 meets the water retainer wall (Fig. 9a). As the geometrical accuracy of the parts was also not exactly known, 10 mm wide radial seams were designed between them. Notwithstanding these precautions, the final closing part (6 in Fig. 9a) initially did not fit and therefore several parts had to be slightly repositioned.

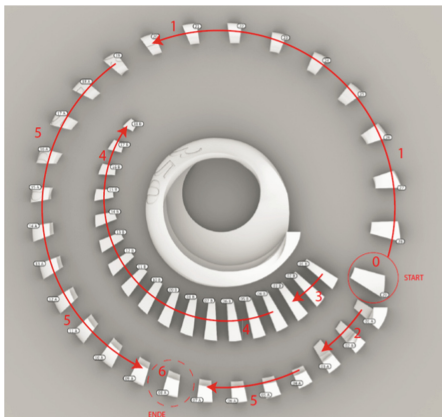
After placement, all parts that had a height to depth ratio > 1 were mechanically bolted to the FRC foundation to increase the global safety, even though the radial geometry and the low center of gravity caused by the multiple layers at the bottom provided stable conditions for the parts even without this fixation. When the positioning of all parts was approved, the radial seams were filled with a flexible silicone of a colour that matched the print mortar as closely as possible.

Additive manufacturing of elements itself is in general quite precise, but the assembly of elements to bigger architectural systems and structures still involves a lot of handcrafting. Very little is known about the accuracy that can be achieved in 3DCP projects. To evaluate the overall precision of the COHESION pavilion, photogrammetry

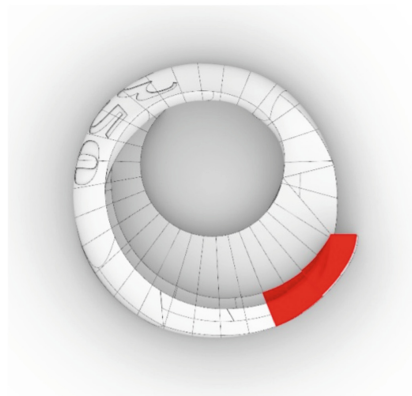
and 3D laser scanning were applied to measure the geometry [3]. Traditional measurements methods as well as 1D laser measuring methods are insufficient to assess the accuracy. The scans showed that only a four elements deviated more than 12 mm from the digital design (Fig. 9b). A more extensive analysis of this topic is planned for a future publication.



Fig. 8. Part No 8a gets lifted with slings by a mobile crane into its position.



(a)



(b)

Fig. 9. (a) Order of Assembly, (b) Photogrammetry and Laser scanning detect elements with slightly increased deviation.

6 Discussion and Conclusions

COHESION surpasses the previously attained levels of volume, size, and particularly geometric complexity of 3DCP structures (Fig. 10). 3D scanning displayed deviations of just a few millimeters occurred throughout the majority of the pavilion. The chosen production method allowed an extremely swift process, taking only 11 weeks from design until opening. It is unlikely this could have been achieved with other manufacturing methods. Very little material was used: compared to a traditional poured concrete structure of the same gross volume, with an average density of $2,200 \text{ kg/m}^3$, the 3DCP technology allowed saving of over 75% of 3d printing mortar. No additional materials such as form work were used. This is an important argument for the future development in the sector of architecture and construction applications in general.

In the weeks and months ensuing the opening, several cracks have appeared in the pavilion structure, likely caused by shrinkage differences or untimely manipulation. The embedded reinforcement ensures the parts remain safe. However, these effects do call for the development of curing guidelines and analysis tools to prevent shrinkage cracks to occur (or allow them in a controlled manner). A future planned publication will include an extensive observation of current condition of the pavilion, after more than a year of exposure to wind and weather in a public space. This will serve as an important test for the further development of building components. The construction accuracy and divergences in the assembly process at the building site and the precision in the production process will be evaluated too.

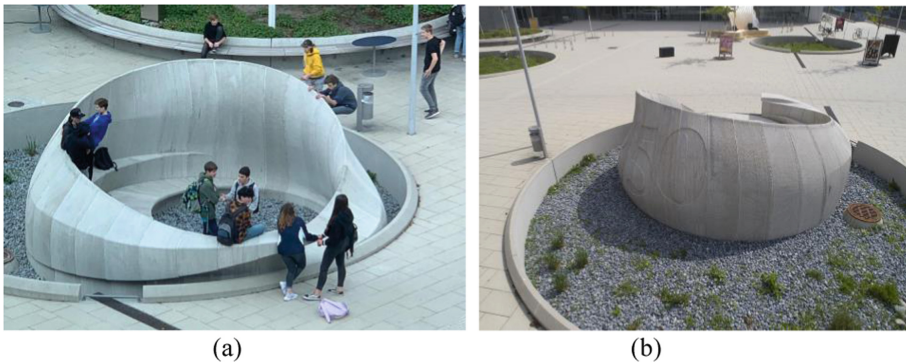


Fig. 10. (a) COHESION pavilion after the opening. (b) Aerial view.

Acknowledgements. The COHESION pavilion was made possible through support from the University of Innsbruck, Baunit, and PORR GmbH.

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Shotcrete 3D Printing Technology for the Fabrication of Slender Fully Reinforced Freeform Concrete Elements with High Surface Quality: A Real-Scale Demonstrator

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Abstract. This paper presents the recent advances in the development of a novel 3D concrete printing technology called Shotcrete 3D Printing (SC3DP). In order to demonstrate the unique assets of this technique a design and fabrication strategy for fully reinforced, double curved concrete demonstrator featuring high surface quality was developed, and is described in detail in this paper. In particular, two topics were highlighted in this demonstrator, firstly the integration of structural reinforcement in both principal directions and secondly an automated surface finishing process for a high-quality concrete surface. This combination of additive fabrication and formative and subtractive postprocessing was demonstrated at the unique large-scale Digital Building Fabrication Laboratory (DBFL) of Technische Universität Braunschweig. The result of this fabrication experiment, a 2.5 * 2.3 * 0.18 m concrete wall element, is finally discussed in relation to the state of the art in 3D concrete printing.

Keywords: Shotcrete 3D Printing · Structural reinforcement · Additive manufacturing in construction · Large scale 3D printing

1 Motivation and Background

Layer-based extrusion of concrete is the most extensively researched and widely-used 3D printing process for the fabrication of large-scale concrete components today. The most commonly used approaches are based either on the Contour Crafting technique [1] or on the 3D Concrete Printing approach [2]. Particularly the latter is today widely adopted by a large community of researchers and commercial players. While several lighthouse projects of complex and intricate geometry have recently been realized on construction scale, there are still process-inherent challenges that need to be addressed in order for 3D printing with concrete to gain a sustained foothold in the construction industry. In addition to still unanswered economic and regulatory questions, the pending technical challenges include the inter layer bonding, the integration of tensile reinforcement, the creation of pronounced overhangs and lastly, the final surface

quality of the printed structures [3]. For each of these challenges, solutions are currently being investigated, including layer bonding through gluing [4], post-tensioning [5], hybrid printing of the support material [6] as well as simultaneous troweling of the surface during printing [7]. In this paper the same set of essential research questions is addressed by using an alternative 3D printing method, the so-called Shotcrete 3D Printing (SC3DP) technique [8].

The SC3DP distinguishes itself from conventional 3D printing with concrete through the fact that the material is not extruded in strands, but rather sprayed with pressure in order to create a 3-dimensional structure. Spraying a dispersed stream of concrete promotes several distinct features. Firstly, through the projection of the material a mechanical layer intermixing and hence intense layer bond is created [8]. Secondly, through spraying, the concrete flows around structural reinforcement and embeds it [9]. A third feature made possible by the previous ones is that Shotcrete 3D Printing allows the creation of pronounced overhangs by gradually transitioning from the horizontal to the vertical printing plane [10]. Finally, due to the ability of the shotcrete to adhere to vertical surfaces a second layer of concrete can be sprayed onto vertical surfaces and can subsequently be smoothed automatically. Based on these specific features of the SC3DP technology a distinct printing strategy was developed and demonstrated through the fabrication of a fully reinforced, double-curved concrete element with high surface quality.

2 Experimental Setup

2.1 General Fabrication Strategy

To enable the full load-bearing capacity, a complete embedding of the continuous structural reinforcement in both vertical and horizontal direction must be provided. For this, a specific built-up strategy has been developed, comprising five consecutive fabrication steps. The key feature of this strategy is that a slightly undulating version of the intended surface geometry is printed in segments with a predefined height (Fig. 1a). The height of these segments as well as the number and amplitude of the undulations can be adjusted parametrically. After each segment is completed, a pair of pre-bent horizontal rebars is placed close to the perimeter of the structure, resting only on the tips of the undulations. This creates closed loops between the concrete structure and the reinforcement, which, over the entire height of the wall, form vertically aligned channels (Fig. 1b). These are subsequently used for the insertion of the vertical reinforcement from above (Fig. 1c). In a forth step, a second layer is then sprayed vertically onto the reinforced core structure (Fig. 1d). This second layer serves both, to embed the reinforcement structurally and as a foundation for the final surface finishing using an automated troweling process.

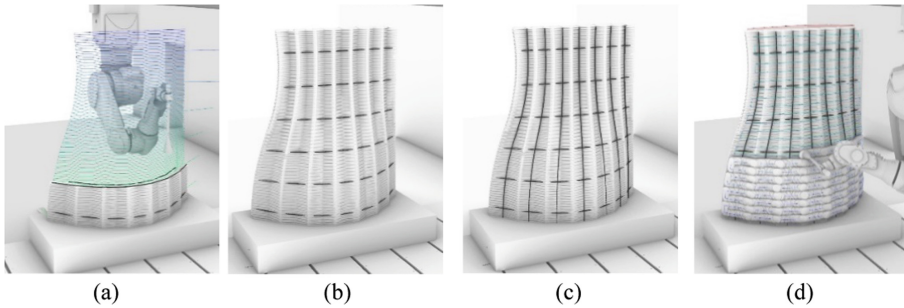


Fig. 1. Built-up strategy; (a): printing of the undulated core and placement of the horizontal pre-bent reinforcement bars; (b): printed core with horizontal reinforcement at full height; (c): inserted vertical reinforcement; (d): covering the reinforcement with an additional layer of shotcrete.

2.2 Fabrication Setup

Robotic Setup. For fabrication the unique Digital Building Fabrication Laboratory (DBFL) of the Institute for Structural Design at TU Braunschweig was used. The DBFL is a large-scale robotic fabrication facility which contains two gantries, each with vertical axes attached. One of which is equipped with a 6-axes Stäubli robot, and the other with a 3-axes Omag milling application. The overall cooperative build space encloses $10.5 * 5.25 * 2.5$ m. The DBFL facilitates the fabrication of large-scale structures, both by subtractive machining, as well as by additive manufacturing processes.

A customized robotic end effector for printing was developed by the Institute for Machine Tools and Production Technology (IWF) based on standard shotcrete printing equipment. This end effector includes a series of custom inlets for the injection of shotcrete accelerator as well as a laser system that measures the distance between the spray nozzle and the printed structure. The latter is used for online process control, regulating the speed of the robot and hence the layer thickness. Additionally, a pneumatic pinch valve was incorporated in order to rapidly stop and start the concrete flow during the spraying process.

Material. Regarding the concrete, a pre-packed high strength repair mortar was used. In order to accelerate the concrete, and enable high early strength and high printing rates, 5% of shotcrete accelerator was mixed into the airstream at the spraying nozzle. Whereas, this concrete is suitable for many SC3DP applications, currently also a purpose designed, customizable concrete mix is being developed by the Institute of Building Materials, Concrete Construction and Fire Protection (IBMB) [11].

For reinforcement, standard 10 mm B500B steel rebars were used. The horizontal rebars were pre-bent using a manual rebar bending machine. For ease of placement, additionally 6 cm long pins were welded to the rebars (Fig. 2b).

Design and Control. To establish a seamless digital workflow from design to manufacturing, the parametric visual programming interface Grasshopper for Rhino 3D was used. In this particular workflow the 3D surface geometry was generated using parametrically variable input curves. Based on the surface geometry the undulations were generated parametrically and the geometry was structurally analyzed for fabrication feasibility, e.g. regarding the ability to printed without collapsing. For this, the Grasshopper plugin Karamba was used and a simplified material model was applied, representing the loadbearing capacity of the freshly printed concrete. These values were measured in previously conducted parameter studies. The structural analysis indicates areas where the stresses in the wall exceed the material's loadbearing capacity. If an excessive load was detected, the geometry was parametrically changed until the stresses remained within the limits of the material capacity. After a stable configuration was found, the printing paths were generated automatically using a custom written python component. Subsequently the machine instructions were generated using the Grasshopper plugin Robots [12].

Printing Parameters. A chosen nozzle diameter of 15 mm, a distance of 20 cm from the nozzle to the printing plane, an air pressure of 2 bar and a robot speed of 0.25 m/s, resulted in a layer width of 12 cm and a layer height of 1 cm. With these settings a volume of approximately 1 m³/h can be printed.

2.3 Fabrication and Experimental Investigation

Core Printing and Placement of Horizontal Reinforcement. According to the printing strategy described above, the core structure was printed incorporating slight undulations. The number and depth were adjusted parametrically to seven undulations with an amplitude of 5 cm. The height of the segments was set to 40 cm, with the first and the last segment being exceptions. After spraying a base of six layers, the pneumatic pinch valve was activated, immediately stopping the flow of concrete. The robot was moved to a pre-programmed position, clearing the way for manual placement of the first pair of horizontal rebars. The rebars were placed merely resting on the tips of the undulations. After placement, the workspace was cleared, and fabrication continued. The entire procedure was repeated for the remaining segments until the full height of the wall was reached.

Placement of Vertical Reinforcement. After the wall core was printed, the 10 mm vertical rebars were threaded into the loops that were created between the undulating concrete core and the horizontal rebar. Over the length of 2.5 m, the rebar was sufficiently flexible to be inserted without pre-bending, significantly lowering the amount of labor. In total 7 rebars on the front and 6 rebars on the backside were inserted, within approximately 15 min of time (Fig. 3).



Fig. 2. Fabrication process: (a) Shotcrete 3D Printing of the core structure; (b) manually placed, pre-bent reinforcement with additional pins for securing the position.



Fig. 3. Vertical reinforcement: (a) Threading in the unbent vertical reinforcement; (b) close-up from seen from the back side.

Second Layer Printing. Immediately after inserting the vertical rebars, a second layer of concrete was printed vertically onto the core structure entirely embedding the reinforcement. For this the same concrete as for the core structure was used, however as the concrete of the second layer needs to remain malleable for finishing, no additional accelerator was used. In terms of the printing path, a horizontally oriented printing strategy was chosen (Fig. 4). In order to level out the undulations, the robot speed was programmed in relation to the distance to the surface. More specifically, when approaching a valley of the undulation the robot speed was lowered and more material was applied. In reverse, when approaching the peak of a valley the robot speed was increased, adding less material. The application of a cover layer was repeated twice, until a sufficient cover of 3 cm, measured from the peak of an undulation, was achieved.



Fig. 4. Second layer printing: (a) Close-up of the spraying process; (b) slight undulations are still visible after the first pass.

Surface Finishing. The surface finishing process was performed with the five-axis milling portal involving three stages of smoothing. Approximately 20 min after the second surface layer was applied, the still malleable concrete was redistributed using a rotating steel disc with a diameter of 20 cm containing three flexible steel blades (Fig. 5a). For this process, the portal speed was set to 10 m/min and the disc was set to 120 rotations per minute.



Fig. 5. Surface finishing: (a) Vertical finishing using a 20 cm steel disc with blades; (b) horizontal finishing using a 20 cm diameter flat steel disc.

In a second pass, the surface was smoothed with a flat steel disc of the same diameter. Robot speed and disc rotation remained unchanged. As with the previous tool the process was repeated once following a vertical, and once following a horizontal orientation (Fig. 5b). Finally, a plastic disc with a diameter of 10 cm was used to increase resolution and surface smoothness. In a last pass the wall was smoothed in vertical direction from top to bottom.

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Edge Milling. For a precise edge definition, the right and left edges of the wall were trimmed with flank milling process. This process was repeated twice, once before the second layer was applied, and once after. For both passes a flank mill with a length of 20 cm and a diameter of 20 mm was used. The speed was set 7 m/min and 200 rpm. Each edge was cut in one continuous operation (Fig. 6).

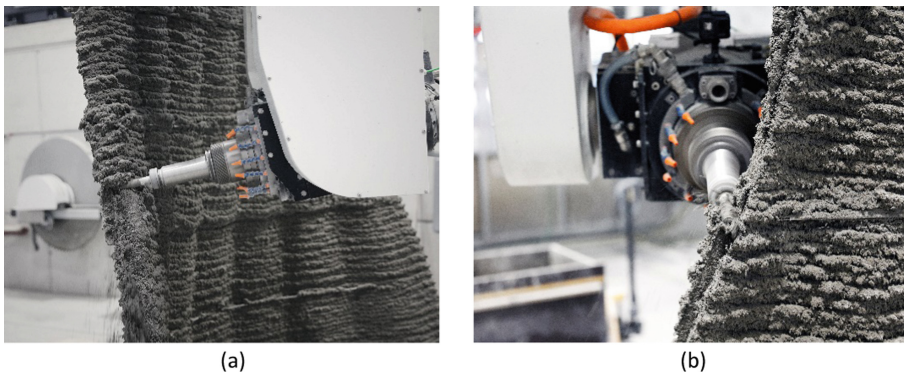


Fig. 6. Edge cutting process: (a) flank milling using the five-axis mill; (b) close-up of the milling process.

3 Results and Discussion

The total fabrication for the $2.5 \times 2.3 \times 0.18$ m wall, from printing start to surface finish took 3 h and 45 min of which 45 min were consumed by printing, 35 min for the placement of reinforcement, 30 min for the second layer printing, 45 min for smoothing and 10 min for edge cutting. The remaining time was used for the preparation of the successive steps. Regarding the digital simulation of structural stability during printing, the producibility of the structure was reliably predicted by the Karamba calculation. The placement of horizontal reinforcement was significantly simplified containing the welded pins, as otherwise the pre-bent rebars showed a tendency to slip down from the concrete core. The prefabrication of the horizontal rebars through manual means, proved to be a time intensive and laborious task. Threading in the vertical rebars on the other hand was fast, precise and unproblematic. Due to the length, the vertical rebar showed sufficient flexibility and did not have to be pre-bent. For more demanding load cases, the amount and density of the reinforcement can easily be adjusted, either by changing the number of undulations, or the thickness or the amount

of rebars per loop. A compelling advantage of this system is that the density of the reinforcement can locally be differentiated, according to the specific load case. During the surface treatment, a large amount of material was redistributed during the first troweling operation, which indicates that the horizontal spraying strategy, slowing down in the valleys and accelerating at the peaks, was not sufficiently precise. In contrast to 3D printing of the core, the online measuring method was not used for second layer printing. However, this would allow the speed of the robot to regulate itself according to the distance to the surface. Thus, only the path but not the speed of the robot would have to be programmed. However, after troweling a smooth high-quality surface was achieved, leaving the last vertical troweling pass subtly visible (Fig. 7).

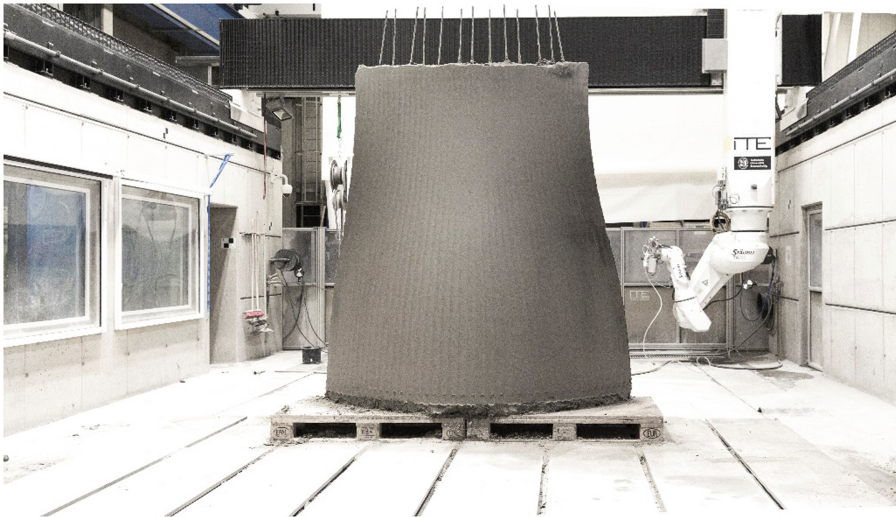


Fig. 7. Finished wall after smoothing and edge trimming

The extent of these visible traces depends on the size of the smoothing disc and how it is mounted on the milling portal. Flexible mounting would allow the disc to adapt more closely to the curvature of the wall. To achieve an entirely smoothed surface, a felt disc or sponge could be used in a final pass. The edge cutting delivered satisfactory results, which could be further improved by grinding the surface at a time when the concrete has further cured. A separate strategy must be developed for the upper edge, considering the protruding reinforcement bars. For geometric quality control, the surface was digitally measured twice using 3D scanning. Once after the reinforcement was installed, and once after surface finishing. Despite the use of the online laser measuring system, a comparison of printed core (without reinforcement) showed geometric deviations of up to 10 mm. Here it is probable that the structure has subsequently sagged slightly under its own weight, which cannot be detected globally by the online measuring system during printing. However, these small inaccuracies

were geometrically levelled out by applying the second layer and finishing the structure with the smoothing discs. In this particular demonstrator the backside was left untreated, showcasing the printing and reinforcing strategy.

4 Conclusion

This final demonstrator showcased the advances made during the interdisciplinary research project “generative manufacturing with concrete”, which involved specialists from the field of architecture, civil engineering, mechanical engineering and material science. Interdisciplinary and experimental research made it possible to fabricate a fully reinforced, double-curved concrete wall with high surface quality using Shotcrete 3D Printing, an alternative approach to extrusion-based 3D concrete printing processes. The demonstrator was specifically designed to showcase the unique capabilities of the Shotcrete 3D Printing method.

In addition to the good layer bonding properties, inherent in the Shotcrete 3D printing process and the extended geometrical freedom, two other main features of the process are the capacity to integrate reinforcement, and the automated surface finishing. Regarding the reinforcement, in this demonstrator the steel bars are continuous in both principal directions following exactly the geometry of the double-curved wall. This was enabled, through a unique reinforcement strategy, where the concrete supports the horizontal reinforcement in its spatial position, creating loops for the vertical reinforcement to be threaded through. Without pre-bending, the vertical reinforcement can follow geometrically complex, i.e. non-orthogonal, trajectories.

Moreover, the reinforcement is structurally fully embedded by means of the second layer printing routine. Hence, the second layer printing routine is not only contributing to the aesthetic qualities, but is rather an essential part for fostering the structural integrity of the system. In future research the automatization of the reinforcement will be addressed. For this also other material processes, as for example the use of robotically placed, continuous fiber placement will be addressed. Regarding the second layer printing and troweling process, the digital capacities for surface finishing go well beyond smooth surfaces. Here a variety of other digitally controlled surface structures, for example by means of formative, subtractive and additive processes, will be investigated.

In summary, the demonstrator showcased that Shotcrete 3D Printing is a viable addition to the more widely studied extrusion-based 3D printing approaches with concrete, especially for the fabrication of structural elements where high geometric resolution only plays a subordinate role.

Acknowledgements. This final demonstrator is the result of a four years collaboration between Technische Universität Braunschweig (Institute of Structural Design (ITE), Institute of Building Materials, Concrete Construction and Fire Protection (IBMB), Institute of Machine Tools and Production Technology (IWF)), Leibniz Universität Hannover (Institute of Assembly Technology (Match)) and Technische Universität Clausthal (Institute of Non-Metallic Materials). The research Project was funded by the lower Saxony Ministry of Science and Culture and the Lower Saxony Technical Universities (NTH). The Digital Building Fabrication Laboratory was

funded through the German Research Foundation (DFG). The Junior Professorship for Digital Building Fabrication is funded by the Gerhard and Karin Matthäi Stiftung. The concrete was supplied by MC Bauchemie. Furthermore, the authors would like to thank Hendrik Lindemann, Niklas Nolte and Roman Gerbers for their contributions during the project period.

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UHPFRC Pavilion of 3-Dimensional Pentagon Tiling

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Abstract. The pavilion of ultra-high performance fiber reinforced concrete (UHPFRC) was fabricated in the form of 3-dimensional pentagonal tiling by wood formwork. Mann/McLoud/Von Derau discovered a 15th monohedral tiling convex pentagon in 2015 using a computer algorithm. Each unit of UHPFRC pentagon in 2-dimensional plane is the same but they are changed into different shapes in 3-dimensional vault type for the pavilion. To generate the 3-D shape two attractor points were located on the ground level. The transformation from 2-dimensional pentagonal tiling into 3-D vault was generated by Reino[®] and Grass hoper[®]. The data of formwork for units of UHPFRC was generated and then fabricated by wood. The fabrication of wood formwork relies on 6-axis robot cutting. To give structural stability of the vault the thickness of lower units was increased. The advantage of flow of UHPFRC enabled us to place UHPFRC into each of wood formworks. The lateral pressure of young UHPFRC was controlled by external screw jacks to avoid the deformation of wood formworks during curing. The connections between units relied on bolts and elastic pads. The connection behavior of bolts to transfer shear was guaranteed by the experimental program for strength.

Keywords: Tessellation of pentagons · 3D surface mapping · Wood formwork · UHPFRC

1 Introduction

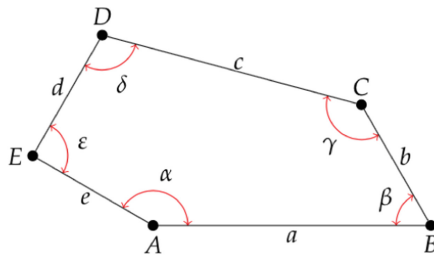
The excellent performance of ultra-high performance concrete (UHPC)-when compared with normal-strength concrete or even high-strength concrete- is predominantly due to its denser hardened cement matrix. The development of especially efficient superplasticizer enabled the production of concrete with a high proportion of optimally tightly packed fine particles and an extremely low water/binder ratio about 0.2 in an easy-flowing consistency (Fehling et al. 2014). The high flow at fresh UHPC enables us to generate free-form shape of concrete with appropriate form-work. Digital concrete has diversity depending on process and concrete material. This paper presents application of ultra-high performance fiber reinforced concrete (UHPFRC) for pavilion construction using complicated wood formwork. This project aimed to demonstrate advantage of UHPFRC by generating free-form architecture. The advantage of

UHPFRC is easy-flowing of fresh concrete for pouring into formworks of free-form concrete architecture. To achieve the free-form concrete construction the formwork fabrication for concrete is critical.

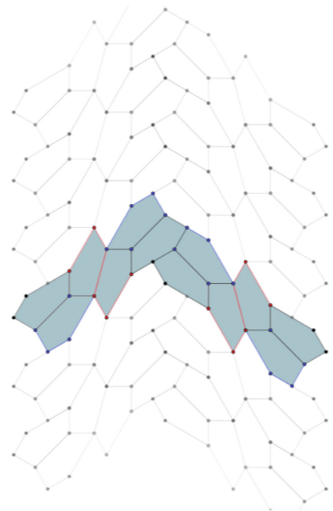
2 Pavilion Design

2.1 Tessellation of Pentagons

Tessellation or tiling has widely provided various architectural patterns. A tessellation of a flat surface is the tiling of a plane using a polyhedron or more other with no overlaps and no gaps. Tessellation has great potential for free-form architecture due to extremely complex shape generations by precise rules and orders (Chang 2018). This research demonstrates how to apply tessellation of pentagon of plane to UHPFRC 3-dimensional pavilion construction (Fig. 1).



$$\alpha = 150^\circ, \beta = 60^\circ, \gamma = 135^\circ, \delta = 105^\circ, \epsilon = 90^\circ \text{ and } a = 1, b = 1/2, c = 1/(\sqrt{2}(\sqrt{3}-1)), d = 1/2 \text{ and } e = 1/2.$$



(a) Unit of 15th monohedral tiling convex pentagon

(b) 12 tile primitive unit

Fig. 1. Type 15th monohedral tiling convex pentagon (<https://www.npr.org/2015/08/14/432280676/scientists-discover-15th-convex-pentagon-able-to-tile-a-plane>)

The recent tessellation of 15th monohedral tiling convex pentagon in 2015 discovered by Mann/McLoud/Von Derau (<https://www.npr.org/2015/08/14/432280676/scientists-discover-15th-convex-pentagon-able-to-tile-a-plane>) is shown in Fig. 2. In this project this 2-D tessellation can be mapped into 3D surfaces of structural units with the boundaries of arches and supports on the ground.

2.2 From 2D Tessellation to 3D Surface Mapping

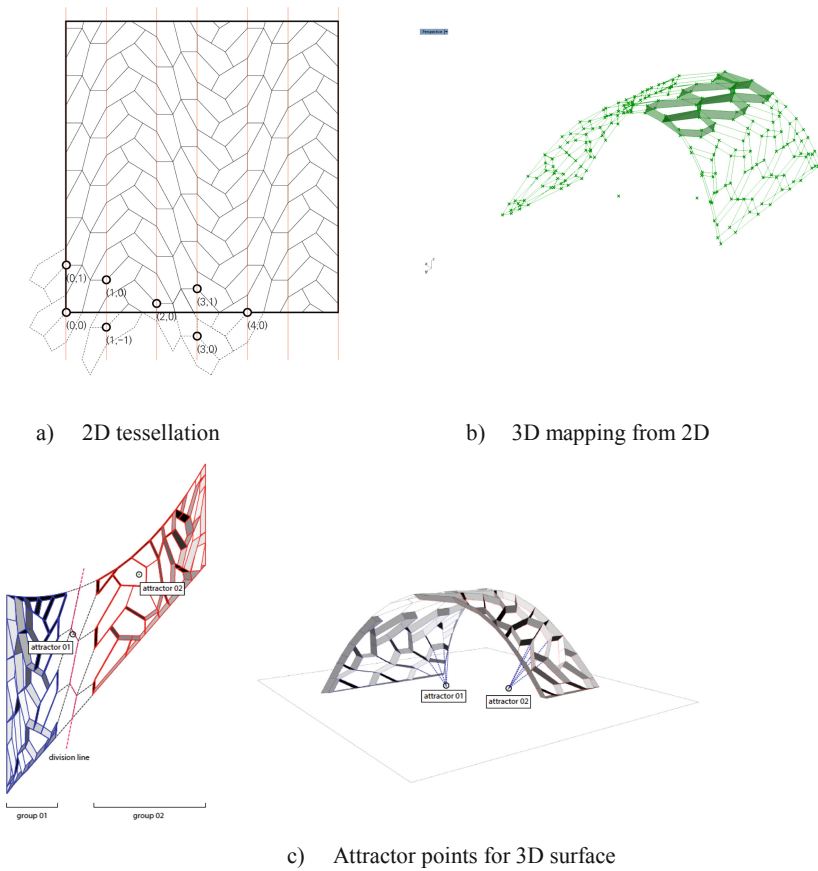


Fig. 2. 3D surface

To transform 2-D tessellation of 15th type pentagon into 3-D cylindrical vault a new coordinate system parallel to the axis of vault is arranged as shown in Fig. 2 (a). UV mapping is the 3D modelling process of projecting a 2D image to a 3D model's surface such as texture mapping (https://en.wikipedia.org/wiki/UV_mapping). Several units of pentagon were cut-off along the boundaries. Two reference points on the ground were set as attractor points for meeting points of five panel surfaces of every pentagon unit in two groups.

For a small pavilion to be constructed out of UHPFRC we needed to find a computational design solution to map a tessellation of a 2D-plane to a surface in 3D-space, and consequently turning the mapped tiles into 3D structural units, subject to the constraint that the structural units are composed of planar segments only. This latter constraint was taken up as part of the design intention, and the formwork elements were fabricated out of simple wooden elements using CNC techniques after investigation of possibility of other materials such as steel, EPS, and gypsum plaster.

3 Formwork Fabrication

3.1 Formwork Design

From the form finding process for the pavilion to the modeling of the formwork, the complete process has been carried out and carefully recorded using computational design techniques. Parametric modeling system using Grasshopper and Python scripting was used to explore various design and formwork options and it also allowed for all data to be stored and reviewed simultaneously. Furthermore, adhering to a parametric design methodology throughout the whole design process enabled complex form modeling exploration and editing (Fig. 3).

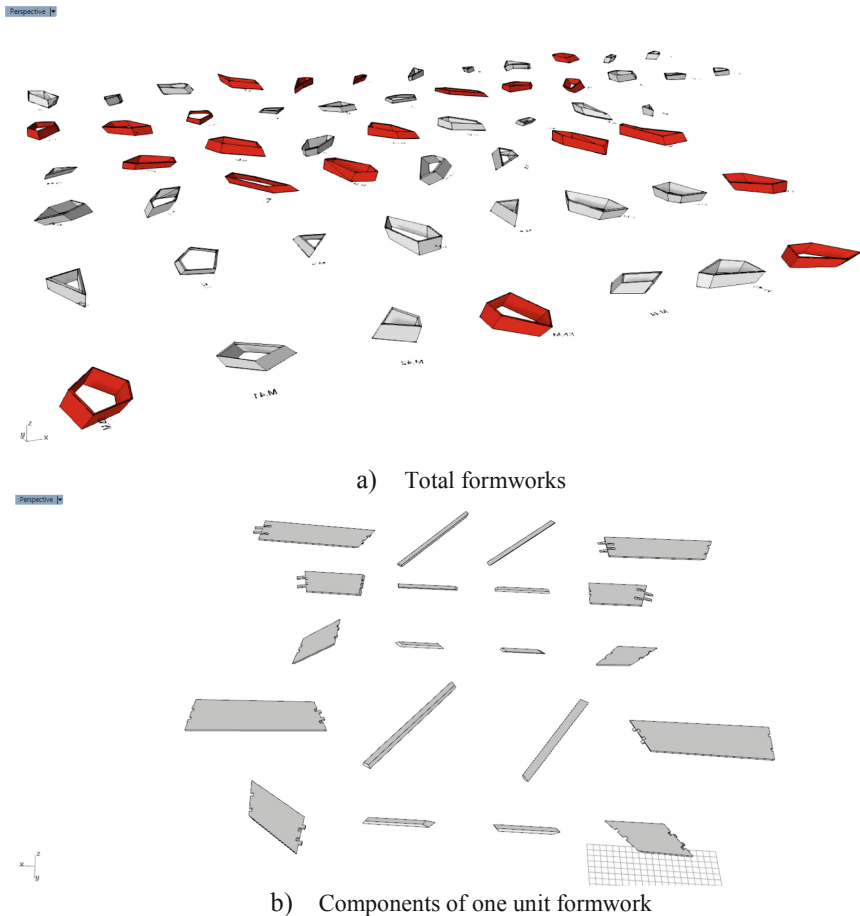


Fig. 3. Formwork units for UHPFRC

Due to the boundary constraint all of 56 units consist of triangles, rectangular, and pentagon units. To fabricate wood-formwork the vertical finger joints between wood

plates were applied. The thickness of UHPFRC units was designed between two panels by 18 mm for inside and 38 mm for stability of plates along the boundaries (Fig. 4).

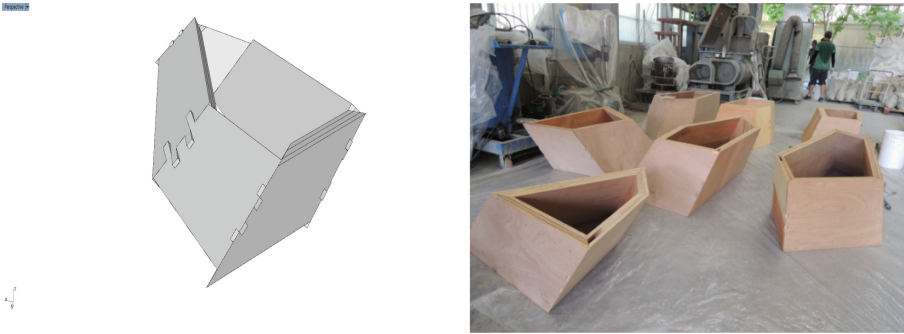
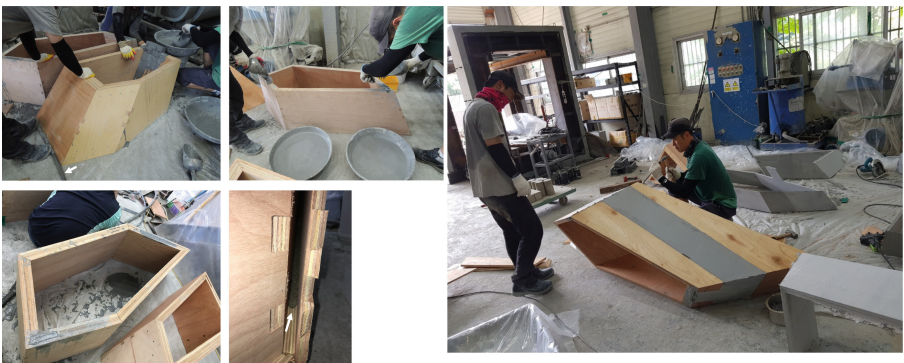


Fig. 4. Wood-formwork for UHPFRC pouring

3.2 UHPC Placing and Curing



a) UHPC pouring

b) Formwork demolding

Fig. 5. UHPC pouring and Demolding

After the wood-formwork fabrication the concrete work was followed in the next step. The UHPFRC pouring and curing as shown in Fig. 5 were critical stage to control the quality units of pavilion. The horizontal level of UHPFRC was set to keep their position of top surface of units. The intended temperature and moisture for curing were kept by a temporary tent for wrapping. After curing the demolding work was carefully finished to keep their forms and surface texture.

4 Bolt Connection Behavior with UHPFRC Panels

4.1 Objectives of Experimental Program for Bolt Connection

To fabricate individual pavilion units for the total system the performance of bolt connections between units was to be investigated. We therefore needed to investigate shear behavior of single and multi-bolted connections with the identification of main failure mechanisms of bolted joints of UHPFRC panels. This experimental program of the multi bolted joints for UHPFRC panels involved direct tensile tests, especially focusing on the relationship between the failure modes, strengths and stress distribution with the variables of the width, edge distance and patterns of bolts (Kwon et al. 2017). Based on the experimental results with analytical approaches, a rational design procedure for predicting ultimate load were proposed in terms of stress concentration factor. The proposed design procedure provided the location and numbers of joints for the pavilion with consideration of the ultimate load and failure modes.

4.2 Failure Modes

The experimental program performed a total of 18 single-bolted joints tested in this investigation. Typical governing failure modes and ultimate strength of single bolt in UHPFRC panels can be identified as cleavage and net tension failure modes depending on edge distance as shown in Fig. 6. The net tension failure modes showed higher strength with limited ductility while the cleavage failure modes lower strength with larger ductility as shown in Fig. 7. Based on this study the connection of single bolts ensured the required shear strength of UHPFRC units of pavilion with allowable edge distance.

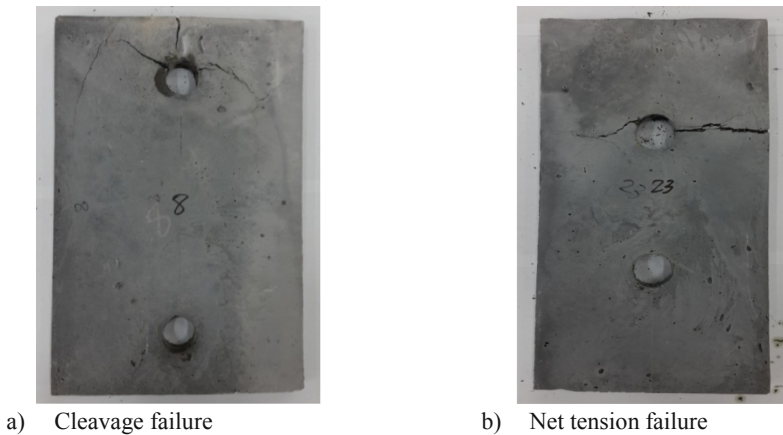


Fig. 6. Typical failure modes of single bolt in UHPC panel

The cleavage failure was characterized by a major crack, parallel to the panel longitudinal direction after major cracks from the hole were developed along the horizontal direction. As the load increased, the crack opened until the ultimate load. From the observation of this mechanism the importance of the fiber orientation around the full hole should be considered. In the net tension failure, a major crack was developed across the center of external holes which controlled the final load-carrying capacity while other subsequent cracks developed as load increased.

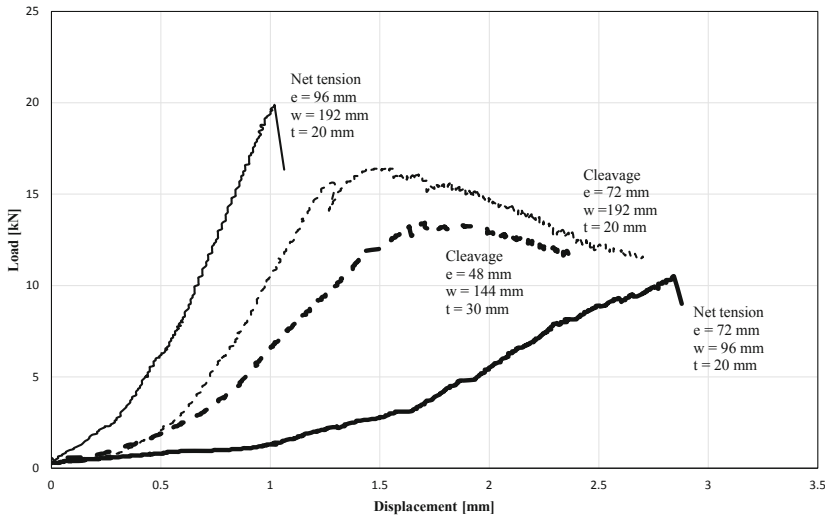


Fig. 7. Tension-displacement relationship of Single bolt connections

5 Fabrication

The pavilion was a research project commissioned by Seoul National University research team as an architectural application of UHPFRC. Using the bolt connection with rubber pads between units the pavilion has been built. Before the construction we simulated 1/8 scale model by 3D printing units as shown in Fig. 8 for the process of construction and structural integration. Temporary falsework and connection bolts were necessary to finish the final fabrication and control the balance between units.

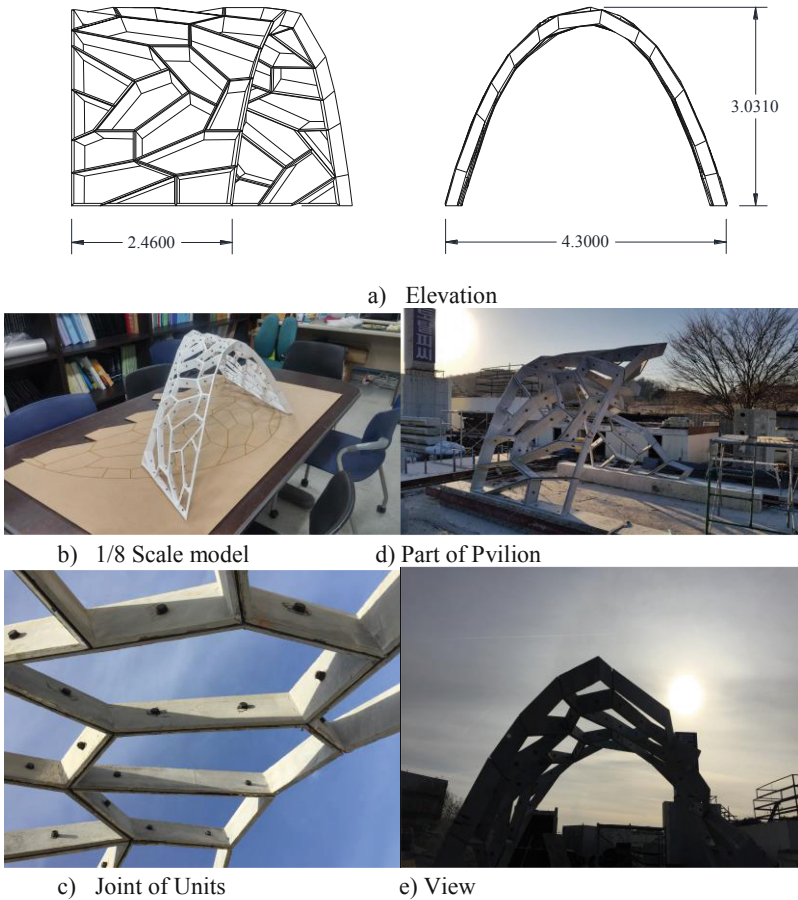


Fig. 8. Completion of UHPC pavilion

6 Conclusion

This project has demonstrated the realization of UHPFRC easy flowing property using complicated wood-formwork fabrication. The latest discovered tessellation of pentagon of plane was converted to UHPFRC 3-dimensional pavilion construction with the investigation of alternatives for formwork using wood, metal, and EPS. The convex pentagon was mapped to 3-D surface of vault shape for the pavilion. The crucial work stage in the project was the fabrication of wood among them. Based on this project we can draw the following concluding remarks:

- 1) The potential application of UHPFRC for free-form architecture via wood formwork can be realized by digital work processes from the design stage, formwork production, to the final fabrication.

- 2) The digital concrete processes require geometrical interpretation of architectural shapes, understanding of material properties of concrete, curing of UHPFRC in formworks, and structural behavior of systems and components.

Acknowledgment. This work is supported by the Korea Agency for Infrastructure Technology Advancement (KAIA) grant funded by the Ministry of Land, Infrastructure and Transport (Grant 20AUDP-B121595-05). The Institute of Engineering Research in Seoul National University provided research facilities for this work.

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Field Considerations for Deploying Additive Construction

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Abstract. While the additive construction printing systems and applications have grown in size, number and types, they represent and benefit specific needs of individual programs or business interests. Work of start-up companies, construction firms, and research institutions has focused on applications for the commercial construction industry. The development of printing systems are directly connected to the application. Each application requires a different range of mobility, from stationary machines to machines capable of being setup in minutes instead of hours. These printers are based on pre-existing equipment types including gantry, robotic arm, cable bot, and jib crane. Alternatively, this technology has clear applications for Humanitarian Assistance and Disaster Response (HADR) and military deployed operations. Unique requirements of these operations include the necessity for using highly deployable mobile printers with local or indigenous materials. The US Army Construction Engineering Research Laboratory (CERL) has developed collapsible deployable printing systems, trained military personnel to independently operate these systems, and performed demonstrations using locally available materials with applicable reinforcing methods. The results of this work not only applies to military construction, but to the construction industry. Through larger demonstrations, CERL has started to confront the struggles that the industry faces. These challenges include continuous equipment operation and maintenance cycles, the development of printable mixes with variable local materials, the development of printing systems that can accommodate variations in materials, and applicable construction methods.

Keywords: 3D printing · Additive construction · Deployable · Printer systems · Continuous printing

1 Introduction

The design and construction of any structure requires careful consideration of the construction method, intended use, local resources, and local constraints. This logic applies for commercial construction, as well as Humanitarian Assistance and Disaster Relief (HADR) and military deployed operations. In considering the application of concrete additive construction (CAC), also termed 3D concrete printing, research has primarily been conducted in a controlled environment (laboratory), focused on

materials development [1, 2], the intended uses [3–5], and to a lesser extent on the validation of an integrated construction method [6].

For CAC, the operation planning and design should consider the construction type, printer type, pump type, materials, material delivery, shift length, environmental conditions, reinforcing method, and transportation [6, 7]. Construction type refers to the use of either print-in-place (PIP) or pre-print methods, where these terms are defined elsewhere [6]. Printer type refers to the use of either a gantry, robotic arm, cable bot, or jib crane printer. Pump type refers to the use of a progressive cavity, peristaltic, piston pump, or a custom designed pump or extrusion apparatus.

A wide body of research has been made in researching additively constructed concrete (ACC), the product of the CAC process, defining the qualities that make a printable mortar or concrete. These are the rheological properties (viscosity and yield stress) [8], pumpability [9, 10], extrudability, print stability (buildability), open time [1], layer shape stability [11, 12], shrinkage [13], interface strength [14], and durability. These properties can be used to assess the overall construction quality of the materials and print. Although constituents may vary, printable mixes primarily consist of the base materials (cement, water, and aggregates), a plasticizer, a thixotropic modifier, shape stabilizer, and shrinkage reducing components [1, 13].

Materials development of ACC has focused on proprietary prepackaged materials for printing. While viable for sectors of the commercial construction industry and under certain situations, this introduces difficulties in supply and logistics under a deployed scenario. For example, the shipment of material to the site that is not procured locally can significantly increase costs, and during disaster relief or conflict, may be dangerous as it requires an additional transport, which takes the place of much needed supplies (food, water, power supplies) [15]. Under these circumstances the ability to produce printable mortar/concrete using locally available materials or indigenous materials is critical.

Reinforcement methods for ACC include reinforcing bars (RACC) or Prestressing (PACC). Both methods are viable in regards to constructability and structural performance. The use of fibers is also typically used to enhance the material performance [16]. Additionally, alternative methods of reinforcing have been proposed [16].

The shift length refers to the length that the printer is operated continuously (without stopping). This is critical to the entire print operation, as long print durations can lead to required maintenance or rest periods. Furthermore, environmental conditions can lead to required maintenance, rest times, and material issues [7].

Transportation of printing systems and materials can be critical to HADR or deployed operations. Where printers can either be stationary, transportable, or deployable.

The US Army corps of engineers, Engineer Research and Development Center (ERDC) has been researching deployable additive construction technology since 2015. The research led by the Construction Engineering Research Laboratory (ERDC-CERL), based in Champaign, IL USA has resulted in the development of a deployable additive construction printer system, material that can accommodate for aggregates up to 9.5 mm in size, the completion of 2 buildings (including the first full-scale concrete 3D printed building in the Americas), the first 3D printed bridge in the Americas, and other infrastructure (Culverts, Jersey Barriers, T walls, and military protective items) using

CAC [17]. The following will describe the field considerations for materials, printing systems, and printing operations under various in-country deployed demonstrations.

2 Methods

2.1 Goals and Scope

The goal of this study is to note potential issues with deployed or in field printing operations that are applicable to the wider field of CAC. The scope of this study will be limited to issues that the U.S. Army Engineer Research and Development Center (ERDC) - Construction Engineering Research Laboratory (CERL) has identified during the in-lab and field demonstrations performed. This information is limited based on accounts and documentation of the engineers and scientists on-site. This article focuses on the field considerations for deployable Additive Construction and as such the following does not focus on the specific details of each scenario for brevity.

2.2 Demonstration Sites

Three ERDC-CERL demonstration sites around the United States, depicted in Fig. 1, will be discussed to address field considerations for a variety of environments.

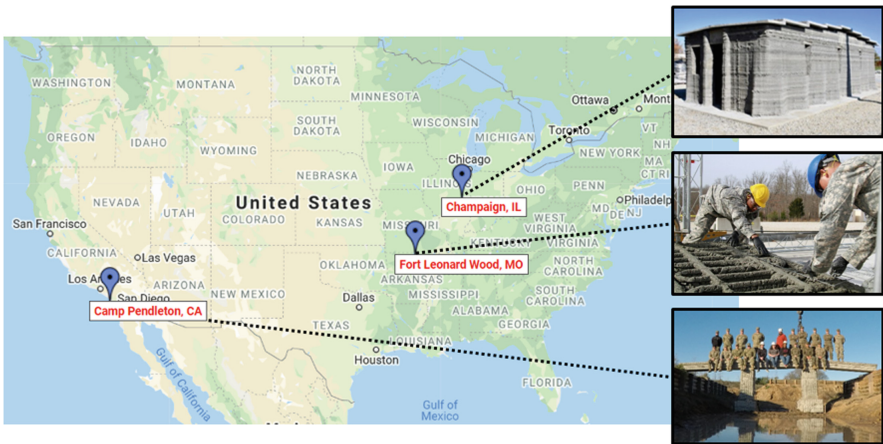


Fig. 1. Demonstration locations: ERDC-CERL Champaign, IL, Fort Leonard Wood, MO, and Camp Pendleton, CA. Map Data: 2020 Google Maps, INEGI.

2.2.1 Champaign, IL

ERDC-CERL's Additive Construction team is located in Champaign, IL. CERL operates and maintains the ERDC Forward Operating Base Laboratory (EFOB-L) to conduct small-scale pilot testing of new technologies. This approximately 68.6 m × 61 m area is composed of compacted gravel, supplied by a flexible power grid capable of running on conventional shore power or generator power, and has a centralized water access

point. This site is also occupied by the “first full-scale 3D printed concrete building in the Americas”, a 512 ft² (47.6 m²) Barracks hut printed in 2017, under cover, as a proof of concept for the technology. This location required no transportation.

Additionally, in August of 2018 researchers and Marines printed a structurally optimized Barracks hut outdoors without cover [6, 7]. This demonstration was a test of continuous day and night printing operations and walls with considerable overhangs (12.5% from vertical). The printing took place over approximately a 48 h time period and tested the equipment for continued use. This print utilized materials local to the Champaign area.

2.2.2 Fort Leonard Wood, MO

In March of 2018, the Maneuver Support, Sustainment, Protection, Integration eExercise (MSSPIX) was held in Ft. Leonard Wood, MO at the Contingency Basing Integration and Technology Evaluation Center (CBITEC). As technologies mature, they are introduced into CBITEC from EFOB-L, where they are evaluated and used by Soldiers, Sailors, Airmen, and Marines undergoing training for future Military missions. This remote area is composed of uneven terrain ranging from soil to loose or compacted gravel, has a generator-powered microgrid, and no water access. Military transport was utilized for transportation of the required equipment to the site.

During this exercise, the team operated for 3 weeks outdoors without cover in a wide variety of weather conditions from snow to 90 °F (32 °C) weather. During this demonstration, United States Army soldiers were trained by CERL researchers to operate the printing system. These Soldiers trained a new unit of Soldiers after only one day of training to operate the equipment with only supervision from CERL researchers. This print utilized materials local to the Ft. Leonard Wood area.

2.2.3 Camp Pendleton, CA

The Steel Knight exercise took place at Camp Pendleton, CA USA during December 2018 outdoors without cover, to create a bridge spanning 33 ft (10 m), which was printed and emplaced within six days requiring only 12 h of print time. This was the first print of a bridge in the Americas, while also being the first print of a bridge in a field environment in the world. This print utilized materials acquired locally from the area surrounding Camp Pendleton. For this location, commercial transportation was utilized for equipment delivery to the site.

2.3 Software and Equipment

2.3.1 Software

The open-source software, LinuxCNC, is utilized on a computer to control the printer's motion. The LinuxCNC program accepts *gcode* files developed during the path-planning process, to execute the printer's translational movement patterns. This program was tailored to the specifications of the 3D printer. LinuxCNC software allows for rapid adjustments to printing parameters, to accommodate for variability in the print operations. This enables features such as fine adjustments to the speed of the print, while mid-operation.

2.3.2 Printer

The printer utilized for the listed demonstrations is a mobile gantry style printer, referred to as ACES Lite. ACES Lite was developed under a cooperative research and development agreement with Caterpillar. This printer was inspired by the original ACES model developed by ERDC-CERL [18]. The printer is capable of being disassembled and stored in a shipping container in 30 min and assembled in 45 min with 2–4 people using simple tools. Once completed, the printer's z-axis is connected via nozzle area to the printer's hose management system. The hose management system is designed to withstand the movement of the printer and the weight of the concrete within the hose during the printing process. The opposite end of the hose is connected to the pump type appropriate for 3D printing and materials composition (Fig. 2).



Fig. 2. Mobile printer-ACES Lite (B-hut print), nozzle, and hoses.

2.3.3 Materials Equipment (Pumps, Hoses, Nozzles, Mixers)

2.3.3.1 Pumps, Hoses, and Nozzles

The material prescription and nozzle size helps determine what style of positive displacement pump (progressive cavity, screw, piston, peristaltic or other) and hose or pipe to use during CAC. Progressive cavity pumps are common in CAC and operate through the rotation of a rotor within a stator to move the material to the discharging port. A progressive cavity pump, Imer StepUp 120, was utilized for these demonstrations with an approximately 2 in (51 mm) inner diameter. Each demonstration had a differing hose length. Due to the desire to reduce complexity, maintenance, and specialized parts, simplistic nozzles ranging from approximately 1.25–2 in (32–51 mm) and varying in shape were used in these demonstrations.

2.3.3.2 Mixers

Prior to material moving through the pump, the material must first be mixed for a prescribed amount of time, including in continuous systems. Concrete mixers allow for large amounts of cement, gravel, sand, water and other components to mix thoroughly without a vast amount of effort from the laborer. There are several types of mixers; some that simply hold and mix added materials and some that store and mix the materials for use (volumetric mixers). A wide variety of mixers were used in these demonstrations including skid steer mounted bucket mixers (Scoop'n'Mix and CAT mixer) and volumetric mixers (Cementech, NASA developed material delivery system, CreteMobile) (Fig. 3).

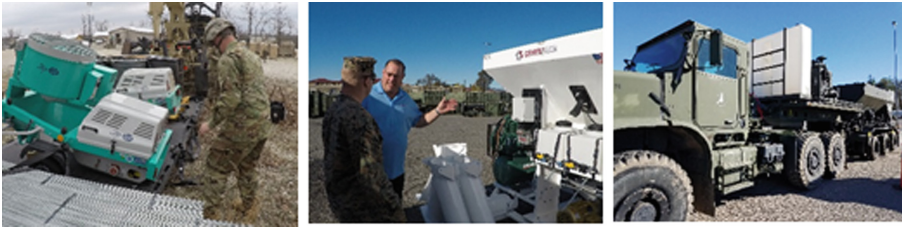


Fig. 3. Pumps and mixers: Progressive cavity pump (Left), CemenTech (Middle), and CreteMobile (Right)

2.4 Materials and Reinforcement

The printable material typically used by CERL was developed to optimize performance with the use of a nominal maximum aggregate size of 3/8 in (9.5 mm) [19]. However, during deployed operations standard mix design will not be the same from location to location. If available in the local area of response (AOR), premix designs would be ideal, however often this is not the case. Therefore, it cannot be stated that a single mix design can be used when the use of locally available materials is desired. It is for this reason that material reconnaissance is necessary during these operations to confirm materials and the determine mix proportions. Material reconnaissance consists of sourcing the available materials that are expected to be used. These materials are sampled in sufficient quantities that allow for determining the aggregate properties (ASTMs), mix proportioning through trial mixtures, and determination of the fresh and hardened properties of the mix. As will be discussed, even with recon the mixture may have to be modified on site based on the stock material variability (Fig. 4).

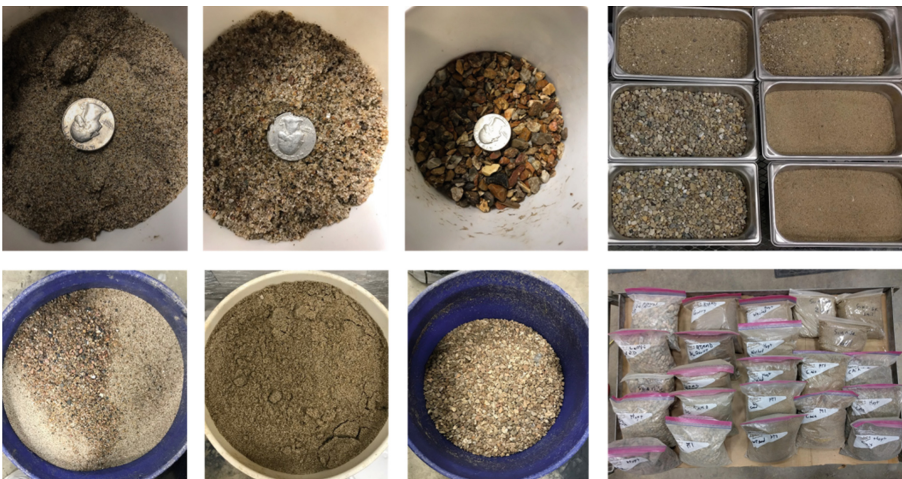


Fig. 4. Aggregate sampling from material reconnaissance using buckets, bags, and trays

Under field conditions the mix proportions varied based primarily on the available aggregate and material availability of each AOR. The printability of a mix relied not on the exact mix proportions, but was verified using quality control tests. A typical field test for performance has been the squeeze test. However, this test is subjective and does not specify direct criteria. More accurate tests for validating printability and layer shape stability are the field rheometer and field unconfined compression test, respectively (Fig. 5). These tests can be used to determine the initial quality of the material, as well as the early age mechanical property development. Additional fresh material tests, not discussed due to their use in standard practice, air content, unit weight, and temperature. Although not covered in the following, hardened properties (Compressive strength, bending strength, interface strength, and shrinkage) are verified to confirm proper material performance.



Fig. 5. Quality control testing: squeeze test (Left), field bucket rheometer (Middle), shape stability test (Right)

Prior to any field deployment, structural design is performed based on the applications and structural requirements of items to be printed. Designs are informed by a number of factors, two of which are the results of the material recon and the reinforcement strategy. The reinforcement that has been used for the demonstrations to be discussed includes grade 60 reinforcing bars, welded wire mesh, ladder wire, and a polypropylene/polyethylene fiber mixture. All of which were acquired from distributors that were local to the AORs (Fig. 6).

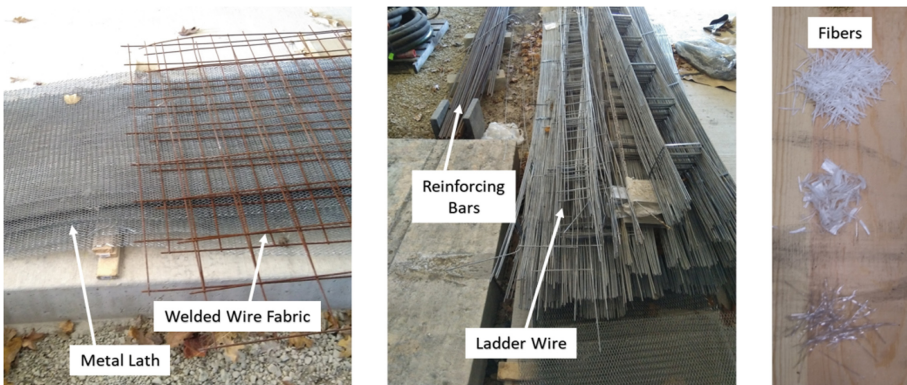


Fig. 6. Reinforcement

3 Results and Discussion

3.1 Site Location

Printing operations varied from each demonstration site. Each site was in different climate zones and weather conditions which played a part in the materials reaction to the environment and weather (Table 1). The acquisition of materials were different and changed the composition of the material prescription. These changes were made in the field and adjusted day-by-day, based on initial material testing completed in the lab.

3.2 Demonstration Challenges and Success

Champaign, IL

Optimized Geometry. Still in the developmental phase, optimizing the geometry and incorporating the feedback from MSSPIX, helped to improve the material investigation and logistics. While still labor intensive, this demonstration proved that a structure's walls could be completed within 24 h, while more realistically within 48 h (a common reference in the CAC field) [7]. The roof proved most challenging. The b-huts' roofs construction was created using typical formwork and cast methods, requiring 6 weeks to complete and 4 days to install. Comparing the time it took to complete a conventional roof (6 weeks) to the CAC walls (48 h) showcases the time savings that could be achieved through further utilization of the concrete additive construction method (Fig. 7).

Table 1. Demonstration conditions

Location	Champaign, IL (Lab)	Champaign, IL (Outdoors)	Fort Leonard Wood, MO	Camp Pendleton, CA
<i>Details</i>				
Material type	Mortar or concrete	Concrete	Concrete	Concrete
Maximum aggregate size (without contaminants)	3/8 in. (9.5 mm)	3/8 in. (9.5 mm)	1/2 in. (12.7 mm)	3/8 in. (9.5 mm)
Construction type	Preprint	Print-in-place	Preprint	Pre-print (near site)
Print surface	Prepared (slab or pallets)	Prepared (foundation)	prepared (slab) and unprepared (gravel)	Prepared (parking lot)
Transportation	None	None	Military	Commercial
<i>Environmental and site conditions</i>				
Time of day	Day	Day and night	Day	Day and night
Lighting	Indoor	Outdoor and tower lights	Outdoor	Outdoor and tower lights
Temperature	Controlled	Hot days and cool nights	Cold and hot days	Warm days and cool nights
Precipitation	None	Sun and rain	Sun, rain, and snow	Sun and rain
Wind	None	Light breeze	Light breeze	Light to moderate breeze



Fig. 7. Structurally enhanced b-hut: roof placement (Left), and completed structure (Right)

Fort Leonard Wood, MO

Real World/Field Conditions, Weather, Printing on Uneveled Surface. In late March through early April during the MSSPIX demonstration. During this time, the team and soldiers experienced extreme temperatures along with angular gravel for the material mixture. To combat the rapid change of temperature, CAC material batches were tested each day to test for buildability. This type of testing commenced throughout the 21-day demonstration as the ambient variation proved to be the deciding factor of the days' print (Fig. 8).



Fig. 8. MSSPIX printing: T-wall (Right), fighting position (Left)

Camp Pendleton, CA

Field Conditions and Integration of Existing Concrete Equipment. With the latest integration of ACES Lite, the team and soldiers created the first CAC bridge in the Americas. The deployable printer traveled over 2000 miles in a 20 ft (6 m) shipping container to Camp Pendleton. Using locally sourced materials, adaptability was crucial in the success of the demonstration. Between Dec 6–11, 2018 (12 h print time), the bridge beams and piers were printed, loaded onto a flatbed trailer, driven 1/8 mile away to the dry gap, and assembled (4 h) (Fig. 9).



Fig. 9. Bridge print: crossing by US Marine (Left), print team (Right)

3.3 Operations

All results below and recommendations are based off of instances during demonstrations where issues occurred or were prevented. The considerations for CAC operations are discussed below and tabulated in Table 2.

Table 2. Concrete additive construction lessons and issue

Category	Lessons and issues
Equipment transportation	Order of preference: No transportation, Military transportation, and commercial transportation Dedicated (Military) transportation was reliable (Fort Leonard Wood, MO) Commercial Transportation was unreliable. Choose reputable company Shipping containers can store more tools/equipment (Camp Pendleton, CA) Flatbed trucks ship less tools and equipment. May need to supplement with separate trailer. (Ft Leonard Wood. MO) On/Off loading must be planned (Crane, ramp truck, Palletized load system (PLS), forklift) Consider methods for lifting, rigging, and pickpoints
Printer system	People wear out faster than machine (Champaign. IL) Consider the use of consumable parts. Use can lead to damaged and required replacement (Champaign, IL) Mixer and pump that are to be used must be determined before deployment Motor issue due to excessive rain and improper installation (Fort Leonard Wood, MO) Design printer components to not require the use of heavy equipment (HE) to assemble. HE may not always be available

(continued)

Table 2. *(continued)*

Category	Lessons and issues
	Designed printer to be lightweight so that each component can be lifted by only two people Component lifting and assembly considerations (Alignment, level of effort, cable management, hose management) Material can change based on curing age, aggregate profile or separation, moisture loss to the system, temperature Hose weight and hose management have an impact on the performance of the printer and print quality (inertial effect)
Printing process	Buildability issues due to operator error in path parameter or Improper design Long hours (Fatigue and morale decrease with increased print duration) Zeroing locations are required to reset or restart print z adjustments required throughout print due to material settlement during over time Build rate must be adjustable based on material properties and may change over the course of a print based on conditions Obstacle and surface avoidance Equipment maintenance time was found to be between 3–4 h Too much lighting is better than not enough
Site	Movable lighting for low light conditions to prevent obstruction Print surface type and conditions (e.g. water pooling on surface (Camp Pendleton)) Construction site conditions and considerations (e.g. soil may be unstable or have low bearing edacity (Camp Pendleton)) Lighting needs to be provided for all major walkways and have minimum requirements (All Demos) Daylight only operations require a minimum of one major light source should be available for extended cleanup times Outside of daylight a minimum of 3 major light sources on the print See text for successful waste management methods Disposable cardboard washout pits were difficult, as materials were hard to separate from pit and were unusable when wet Waste material that is suitable for reuse can be used to create pavers, blocks, used as fill material, or used for on-site needs Concrete recycling requirements may not allow reinforcement or contaminants
Environmental	Temperature must be considered in terms of printing and print team performance and safety Cold temperature can lead to freezing of water in pump and spigot and slowed curing and poor strength gain of material (Fort Leonard Wood). Accelerating admixture may be required. Team could experience frostbite Hot temperatures can lead to overheating of pump, high hose temperature, and accelerated curing of material (Champaign). The use of ice or a retarder may be necessary. Team could experience sunburn or heat exhaustion (Camp Pendleton)

(continued)

Table 2. (continued)

Category	Lessons and issues
Safety	Risk and safety assessment is required to prevent injuries Site inspection should be performed prior to any print or print day A safety briefing should be performed prior to the start of any print Proper personal protective equipment (PPE) should be stated and provided for all personnel Safety concerns include lighting, weather, printer and heavy equipment operation, tripping hazards, breaks, lifting technique Caution tape and cones will prevent observers or pedestrian traffic from entering the construction zone
Materials	Aggregates delivered to site may be contaminated with aggregates from a previous delivery (Fort Leonard Wood) Angularity of aggregates affect printability Sieving may be required depending on size of largest aggregates delivered or contaminants (Fort Leonard Wood, MO) Temperature fluctuations require adjustment of printer settings and mix design (Fort Leonard Wood, MO) Clogging of hose due to aggregate contaminates (Fort Leonard Wood, MO) Clogging of hose due to fiber consolidation (Camp Pendleton, CA) Materials will lead to wearing of pump parts. Parts require replacement over pump specific maintenance cycles Build-up is likely to occur in the mixer, pump, and hose Access to water may be limited due to tile location of print site. Water storage tanks may be necessary

Equipment Transportation. No transportation, Military transportation, and commercial transportation of equipment was found to be the order of preference for transportation. The transport from Camp Pendleton to Champaign resulted in two major concerns: 1) Truck arrived on-site without ramp resulting in delays in shipment, 2) Despite quote for exclusive load, driver moved all the equipment on the trailer and loaded additional items onto the truck resulting in damaged heavy equipment due to improper handling. Recommendation is for transport to be provided by a reputable company or for conducting transport utilizing internal staff.

Printer System. Printer components require careful consideration prior to initiating an operation. This includes the type of printer, pump, mixer, delivery system, and hose management. Improper consideration of items, such as physical and environmental loads, the duration of printing, and printed object properties, can lead to undesirable outcomes. For example, hoses were found to increase in temperature throughout the day and cause setting issues for concrete. Addition of thermal protection on hoses was found to reduce temperature effects. Aggregate consolidation and material build-up was an issue that was mitigated through maintenance cycles and reduction of necking down on nozzles or increasing nozzle size. The extruder nozzle shape, size and standoff distance contribute to the structural performance of CAC. While troweled and more

complex nozzles can give finished appearances, they add complexity in programming and maintenance. Simplistic round or square nozzles often require less upkeep while creating the rounded layer appearance commonly associated with CAC.

Printing Process. The printing process is affected by component print path, print speed, pump speed, software protocols (zeroing and print restart protocols), buildability (constructability) of the print, and duration. Any of these items can lead to errors during the printing process. For example, duration of print time was found to be a personnel, print, and equipment issue. Length of day was found to be an issue when prints were near completion, often pushing times past project planned operation times. Suggest agreeing on go/no go for print times and make contingency plans for if prints are partially completed, keeping in mind potential cold joints. Concrete clean-up is essential to the printing process and may be the most critical to completion of current and the success of future CAC operations, but is not often discussed. Improper clean-up can lead printer component wear, shorter maintenance cycles, and intense labor to remove hardened material for system components.

Site. Site conditions include print surface, soil properties, lighting, and waste water management. Lighting was found to be one of the most preventable issues on a job site. Each demonstration site had differences in lighting varying from two light sources to four. Underutilization of light sources, can result in significant vision impairment which affects the quality of the print and safety for all personnel on-site. When planning lighting, note any tall equipment that may block light and the need for light on all sides of each piece of equipment for maintenance or print issues.

Waste management plans are essential part of site management and must be developed prior to deployment and follow local environmental standards. Plans include site treatment, wastewater treatment (proper pH and particulates or solidification) and proper disposal. Successful waste management options include portable washout pits or containers, washout water treatment containers, berms and tarps to contain spillage, recycling bins for hardened concrete.

Environment. During the planning stage for the demonstration, the print day schedule needs to be determined (as was done for these demonstrations). Cold temperature can lead to freezing of water in pump and spigot and slowed curing and poor strength gain of material. Make sure any printing operations that may occur in cold conditions are properly prepared with heat sources and preventative methods. Hot temperatures can lead to overheating of the pump, high hose temperature, and accelerated curing of material. The use of ice or a retarder may be necessary. In hot weather the team could experience sunburn or heat exhaustion. Printing during hot conditions or prints during the day, provide personnel with sunscreen, water for hydration, proper safety equipment, and enforce breaks. If printing at night is desired, (which can help with dramatic temperature fluxuations) adequate preparation needs to be done to allow for printing operations.

Safety. Before conducting any demonstration a safety and risk assessment needs to be completed to inform all participants of any safety issues prior to engagement in tasks and determination of PPE. Ranges of weather conditions need to be identified for the equipment and print process, for example, certain equipment may not be able to operate

safely in wet conditions. Identify areas for work zones and fence off areas for visitors or viewers; this is easily accomplished with fencing or caution tape and caution cones. If multiple viewers are expected, set up the above zone for traffic flow and assign personnel to assist in guiding.

3.4 Field Materials and Reinforcement

As described in Sect. 2.1, the selection of materials is performed through material reconnaissance and testing. During this process it is critical to properly select the materials that lead to a printable concrete/mortar and can meet structural requirements. During the demos discussed, the selection of admixture, reinforcement, and cement was not a critical issue as they could be easily obtained locally and the quality does not deviate significantly from batch to batch. In regards to cement, there were instances where the type of cement deviated or where the cement was delivered with moisture issues, which would cause issues if not caught during inspection. Reinforcement has not shown to have quality issues, but it must be used for its intended purpose. For example metal lath should not be used as horizontal reinforcement in walls as it has shown to have poor bonding and opening penetration when installed at layer interfaces (Fig. 10).

For a typical printable mix it is sufficient to use a Type I cement, however in regions such as Southern California, USA, where Camp Pendleton is located, it is necessary to use Type V cement to prevent sulfate attack.



Fig. 10. Material quality: reinforcement compatibility (Left) and aggregate angularity (Right)

The materials that have been the most problematic are water and aggregates. Water, if not accessible from a municipal source, must be transported to the site and stored in a tank for use as mix water and clean up water. During MSSPIX, water was stored in a water tender and during Steel Knight water was stored in the volumetric mixer water tank. When water is stored in tanks on site the ambient temperature can lead to elevated temperatures, which can affect concrete curing. On the other hand, freezing temperatures can cause the water in the tank or, as was experienced during MSSPIX, water in the spigot to freeze.

By far, the materials that are the most difficult to control in the field are the aggregates. Although material reconnaissance is performed to decrease material inconsistencies there can still be discrepancies with regards to the maximum size of aggregates, angularity of aggregates, distribution of aggregates, contaminants, and moisture content. During the

MSSPIX demonstration it was not uncommon to find aggregates that were 25 mm or greater in coarse and fine aggregates that were supposed to be limited to 9.5 mm. This may not be an issue in concrete construction, but in concrete additive construction where these particles can be detrimental to the pumps it is a cause for concern. The solution that was developed was a slanted sieve made from wood and wire mesh (Fig. 11).

Aggregate angularity and distribution plays a factor in the mix proportioning for printable concretes and is dependent on the location obtained, the supplier, and whether the aggregate size is crushed or natural. With angular aggregates accommodations in the mix design, for example higher cement content, must be made to develop a printable mix (Fig. 10).



Fig. 11. Oversized aggregates: in gravel (Left), in sand (Middle), and solution for removal (Right)

The moisture content of aggregate materials that are on site is difficult to control. These materials may be delivered in a dry state, oversaturated state, or somewhere in between. Therefore, it is recommended that the moisture content of the aggregates be measured prior to printing to determine the water adjustment for the mix. Careful monitoring of the moisture content should exercise when batching equipment, such as volumetric mixers, are used. As experienced with operations in Champaign, IL and Camp Pendleton, CA, Some equipment models have issues properly measuring the aggregate weight when aggregate materials are in a wet state, where the moisture content is above the saturated surface dry condition.

During CAC operations the quality control tests mentioned in Sect. 2.4 are performed prior to the commencement of printing and at different times during printing. In performing the printable concrete specific field rheometer and layer shape stability tests certain limits can be used to determine the printability of the mix. These limits are determined based on laboratory testing. Once limits have been determined the general plots in Fig. 12 can be used as general guides. For field applications the torque and rotation speed can be determined from either a rheometer or mixer. Torque values for printable mixes will fall between a lower torque limit and an upper torque limit. Torque is typically used due to the ease of determination in the field and soldier familiarity, however rheological properties could be used if desired. The limits are rheometer or mixer specific and therefore will need to be experimentally determined. The shape stability test consists of an unconfined compression test. The gray region is the shape stability zone, which is the region where the material is strong enough to support the load, elastic enough not to tear, yet not so elastic to displace excessively under load.

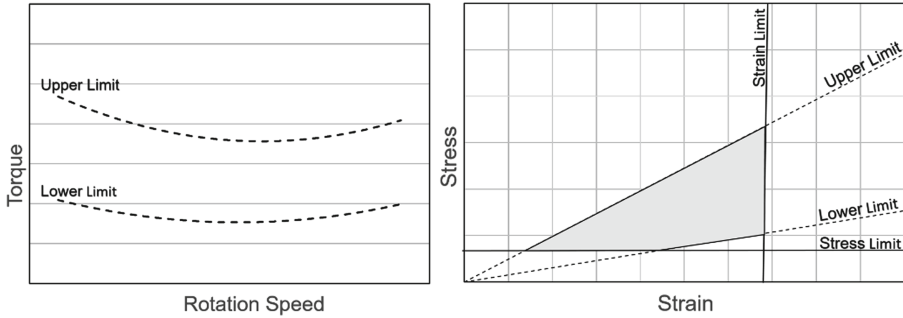


Fig. 12. General printable concrete/mortar quality control test limit plots: shear rheometer (Left), and shape stability (Right)

Other considerations are transportation of the materials to the print site. Since, the demonstrations were in the continental United States this was not an issue. However, under HADR or other deployed scenarios this is not guaranteed.

4 Conclusion

Deployable Concrete Additive Construction (CAC) technology has clear applications for humanitarian assistance and disaster response (HADR), and military deployed operations. However, field applications of CAC differ significantly in process and results from controlled laboratory testing and continued research into the deployability of CAC equipment and process needs to be performed. Durable mobile equipment that can be built expediently with ease and repaired with off-the-shelf parts, delivered to the site with reliable transportation is a key element for deployment. Flexibility with environment, materials, and site conditions is necessary for deploying, as weather conditions can have a profound effect on the equipment, personnel, and the printing process, and the terrain or location can vary depending on the operation, implying that the ability to print on an unprepared surface without cover is to be expected. Prior to deployment, reconnaissance should be performed to assess the site and materials available in the area of response to reduce risk and suitability for printing operations. During this period, the While CAC is automating the construction process, there are many of the same concerns as general construction, this includes quality of sourced materials, site conditions including lighting, soil, and levelness of surface as well as general safety concerns. In performing various demonstrations of deployable CAC operations, where local materials are desired, the key considerations are: equipment transportation, printer system, printing process, site, environment, safety, and material.

Acknowledgements. The projects were supported by the U.S. Marine Corps and the U.S. Army. These efforts were done in cooperation with Caterpillar, U.S. Army Forces Command (FORSCOM) 5th Engineer Battalion, 416th Theater Engineer Command, 419th Movement Control Battalion, the Naval Mobile Construction Battalion 5, Air Force Institute of Technology, and the I Marine Expeditionary Force.

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Sustainable Reinforced Concrete Beams: Mechanical Optimisation and 3D-Printed Formwork

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Abstract. The embodied energy of a building is not only but essentially determined by the quantity of material in its structure. Current fabrication techniques of optimised reinforced concrete (RC) structural elements have not proved sufficient economic competitiveness to be broadly accepted by the construction industry. This partly explains why the construction industry has not yet been able to reduce the embodied energy of newly-constructed buildings or civil works. However, most of the researches driven in the academic world on digital fabrication with concrete are focused on the construction of non-standard structures. The application of digital fabrication to standard structures could help bridge the gap between the need for lower-carbon structures and the economic interest of players in the construction industry.

This paper questions the compatibility of existing building codes with digital manufacturing techniques and presents a novel method for the fabrication of sustainable optimised reinforced concrete beams, compliant with EN 1992-1-1 design requirements.

Keywords: Digital fabrication · Concrete printing · Reinforced concrete · Structural optimisation · Strut and tie method

1 Introduction

Reinforced concrete (RC) construction, whether it is for buildings or civil works, is still arguably comparable to crafts. Burdensome and time consuming site work directly impacts the design of RC elements. Structural engineers often tend to simplify their design to ease the fabrication process on the one hand, and to avoid possible dramatic fabrication mistakes on the other hand [7]. RC structures built at the beginning of the XXth century when concrete was an expensive resource, such as bridges from Maillart [4], however prove the possibility to build lighter sustainable structures. Two pathways with different time frames can be explored if we are to save inefficiently consumed concrete. The long term research line

concerns the exploration of mechanical optimisation applied to RC elements outside the bounds of the current standards both from a purely theoretical [2, 5, 8] and applied [3] point of view. In the shorter term, some standard compliant solutions can be found.

This paper presents a new design and fabrication workflow that takes advantage of digital fabrication to manufacture Eurocode 2 compliant optimised beams. By using 3D printed concrete moulds to exclude the hollow parts of truss-like beams, we are able to address the geometric complexity of the formwork. This process drastically reduces the waste as compared to those that would be produced with a traditional formwork. Section 2 introduces the design methodology based on a strut optimisation approach. Section 3 presents the fabrication of a 3-meter-long beam illustrating the feasibility of the proposed method. Eventually, in Sect. 4 we discuss the potential material savings at stake as well as the levers to enhance the fabrication process in the perspective of its application in the industry.

2 Design Methodology

2.1 Computational Workflow

The whole design and fabrication process is automated under the computational workflow presented in Fig. 1. Based on design requirements, a preliminary EC2 calculation results in the generation of a family of optimal designs from which one is selected based on material savings and manufacturing considerations. A finite element assessment of this design, not included in this paper, could then be provided before the fabrication phase. This paper focuses on the printing of the formwork which is therefore the only criterion considered to assess the constructability of the design. As discussed in Sect. 4.2, more criteria would have to be taken into account for industrial applications.

2.2 Reinforced Concrete Beam Design According to EC 2

Traditional RC beam design involves three main steps. Firstly, longitudinal reinforcements are calculated based on mid-span section equilibrium considerations at ULS, SLS requirements such as maximum displacement, crack opening, rebar and concrete constraints, as well as constraints on the position of the rebars and their total volume. Subsequently, shear reinforcements are calculated to provide minimum shear resistance at ULS. The calculation is performed with discrete values of shear force taking the minimum design value V_{Ed} over a beam portion with a length of $z \cot \theta$ (see Fig. 3 for notations). Lastly, it is possible to perform longitudinal rebar curtailment. In practice, this step is often neglected so as to simplify the rebar cage preparation. It is worth precisising that although minimal steel sections are structural requirements' consequences, effective reinforcement is highly impacted by the geometric constraints (notably the width of the beam) as well as the fabrication method.

As presented in Fig. 2, we propose a new EC2 compliant approach for the shear design of RC beams. This approach is detailed in Sect. 2.3.

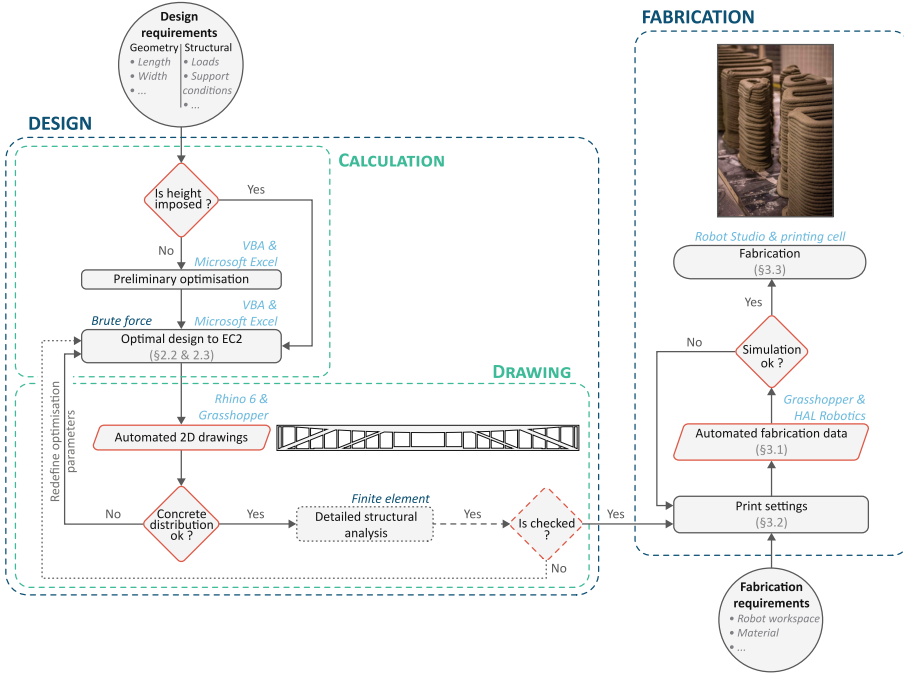


Fig. 1. Computational workflow for the design and fabrication of RC beams according to the strut optimisation approach.

2.3 Shear Strength of Reinforced Members in the EC 2

The shear strength design methodology prescribed by the EC2 for RC elements is based on the Variable Strut Inclination Method (VSIM) [1] applied to a strut-and-tie model of the given element, see Fig. 3. In this method, derived from the first truss analogy models proposed by Ritter [9] and Mörsch [6] the direct contribution of concrete to the shear resistance is ignored. The shear strength of the element is thus given by the minimum between the compressive strength of the concrete (namely the struts, Eq. 1) and the tensile strength of the stirrups (namely the ties, Eq. 2).

$$\begin{aligned}
 V_{Rd,max} &= \sigma_c b_w \cos\left(\alpha + \theta - \frac{\pi}{2}\right) l_w \sin\theta \\
 &= \underbrace{a_{cw} \nu_1 f_{cd}}_{\text{max. stress}} \underbrace{b_w z \frac{\sin(\alpha + \theta)}{\sin\alpha}}_{\text{width and height of the strut}} \sin\theta
 \end{aligned} \quad (1)$$

$$V_{Rd,s} = \frac{A_{sw}}{s} f_{ywd} z (\cot\theta + \cot\alpha) \sin\alpha \quad (2)$$

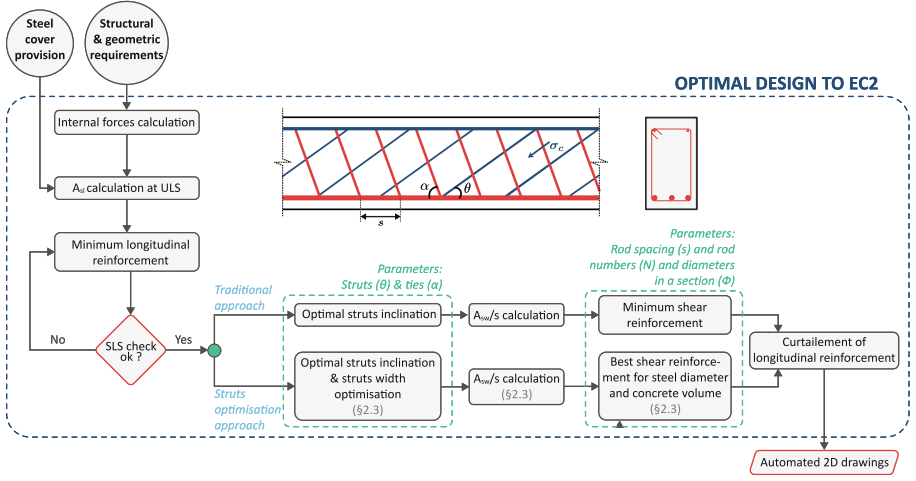


Fig. 2. Eurocode 2 beam design workflow.

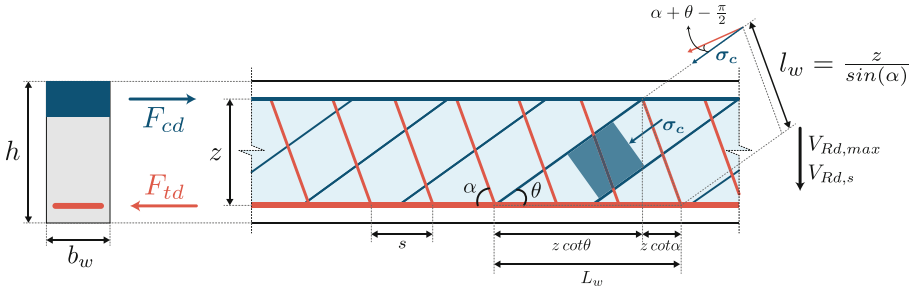


Fig. 3. Eurocode 2 strut-and-tie model for RC elements with shear reinforcements.

In the spirit of the EC2, an engineer is only given design freedom through the choice of the inclination of both the struts ($21,8^\circ \leq \theta \leq 45^\circ$) and the ties ($45^\circ \leq \alpha \leq 90^\circ$) within some empirically determined limits. All other parameters values are set by the mechanical properties of the materials: f_{ywd} and f_{cd} , by the state of stress in the section: a_{cw} and ν_1 , and by the geometry of the section and the previous design steps: b_w and z (inner lever arm for a member with constant depth).

In practice, an engineer would first optimise A_{sw} by properly defining the number and diameter of rods in a section as well as the spacing s between two reinforced section. He would then checks if $V_{Ed} \leq V_{Rd,max}$. Otherwise, he would increase the strut angle θ . However, as written in Eq. 1, the strength of the struts involves the compressive strength of the concrete as well as their width and depth providing one the opportunity to optimise b_w and z . Our design proposal is based on the struts' height optimisation. The minimum strut height is thus given by

Eq. 3. Figure 4 presents a schematic representation of a beam designed with this method and following the steps detailed in Sect. 2.2.

$$z_{opt} = z \cdot \frac{V_{Ed}}{V_{Rd,max}} \quad (3)$$

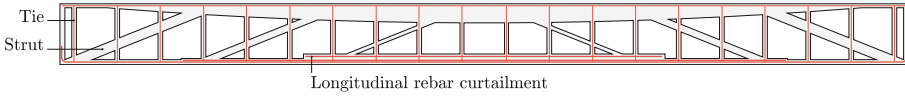


Fig. 4. Schematic representation of a beam designed with the strut optimisation approach.

The next section presents the fabrication of a prototype designed with the strut optimisation method.

3 Case Study: Concrete Printed Formwork for a 3 m-Long Beam

3.1 Automated Fabrication Data Generation

The beams design according to EC2 is carried-out on Excel-based calculation sheets developed by ISC. The results are then exported to Grasshopper. A first set of ‘shop’ drawings is automatically generated to check the concrete distribution on the one hand and serve as a basis for the fabrication data generation on the other hand. From this stage, everything is managed with the HAL Robotics plug-in using Rhino 6 to visualise the data. Hence, the workflow is fully automated from the calculation to the export of the robot procedure. Figure 5 features some examples of 2D beam drawings automatically generated with the workflow.

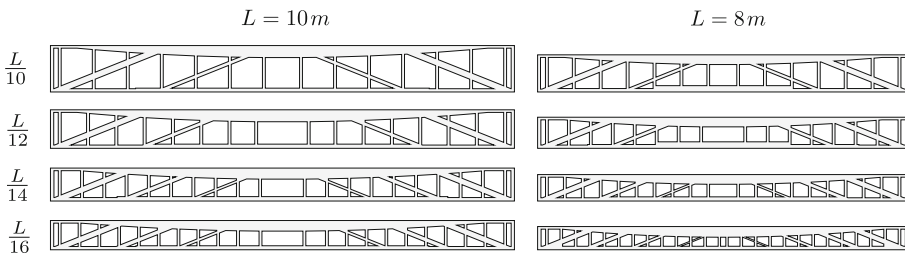
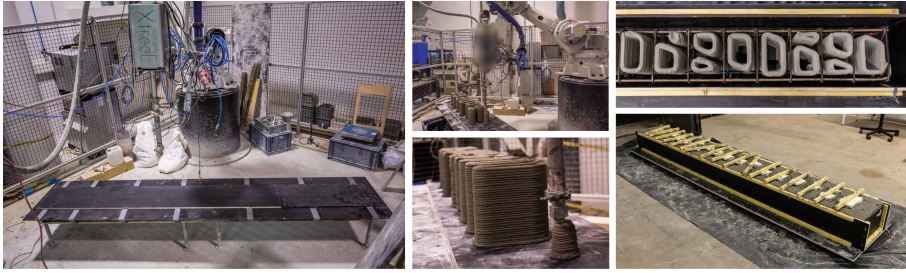


Fig. 5. Benchmark of automatically generated ‘shop’ drawings.



(a) Fabrication of the prototype with, from left to right, preparation of the printing cell, printing of the formwork, final preparation of the formwork and, pouring of the concrete



(b) Demoulding of the beam

Fig. 6. Fabrication of the 3m-long beam prototype

3.2 Experimental Setup and Fabrication

The fabrication process can be divided into two parts: the preparation of the formwork and pouring of the concrete. The formwork contour and lost casing were made with sheets of plywood while the inner formwork pieces were directly printed on the lost casing within our 3d concrete printing cell equipped with a Xtree printing head. The Xtree's technology demands to keep a constant time frame between each extruded layer. For such an application, this time constraint raises issues in terms of concrete and accelerator flow rate management as well as for the robot speed. For instance, for the prototype, the ratio between the longest printed piece perimeter and the shortest one was of 4.46. However, pouring concrete remained the biggest challenge. It is well known that the EC2 includes a large amount of rules driven by the need for the concrete to set evenly in the formwork: minimum spacing between the rebars, etc. Here, the narrowness between the rebar cage, the printed pieces and the plywood sheets augments the necessity for carefully formulating the concrete. For this case study, typical distances between the surface of two printed pieces were of 6 cm with a rebar (HA 6) in between. Our objective was to reach a slump value high enough for allowing us to manually vibrate the concrete and avoid the drift of the blockouts on the lost casing, but low enough to avoid segregation. Table 1 presents the concrete mix, a bill of materials as well as the production rates.

Table 1. Concrete mix (top left), bill of materials (top right) and production rates (bottom)

Gravels (kg/m^3)	890	Printed concrete (kg)	93
Sand (kg/m^3)	876	Poured concrete (kg)	359
CEM II 32.5 (kg/m^3)	395	Steel ratio (kg/m^3)	66
Water (kg/m^3)	191.5		
		Printing (min)	80
		Casting and finishing (min - est.)	120
		Rebar cage preparation (min - est.)	30

Despite our attention, the initial concrete mix was too dry: we probably didn't measure the moisture content in the sand and gravels on representative batches. However, we choose not to add too much water in order to guaranty a minimum strength. Finally, we were able to decently pour the mix inside the formwork.

The next section tackles the potential material savings and the fabrication implications at stake.

4 Discussion on the Potential Material Savings and on the Fabrication Process

4.1 Potential Material Savings with the Strut Optimisation Approach

Loads and Material Properties. All the beam designs presented in this section were done with the same hypothesis. The beams are considered to be simply supported and are subjected to uniformly distributed dead and live loads. The dead loads include the self-weight of the beam and that of a 17 cm thick concrete slab with a span of 5 m. The live loads have a characteristic value of 1.5 kN/m². Appropriate ULS and SLS combinations are taken into account. We consider a concrete of class C30/37 with a density of 2500 kg/m³ and a steel of class B500B.

Optimisation Results. Figure 7 presents ratios between concrete volumes in beams designed with the strut optimisation approach and those of their equivalent prismatic beams. The evolution of this ratio with the span is read horizontally while its evolution with the slenderness is read vertically. The smaller the dots and the lighter the shade, the lower the ratio. And, the lower the ratio, the higher the concrete savings.

As expected, the potential concrete savings increase with the span and the slenderness. Some a priori unpredictable peaks can however be observed (11m - L/10 and 12m - L/15 for instance). Those peaks reflect the way the effective shear

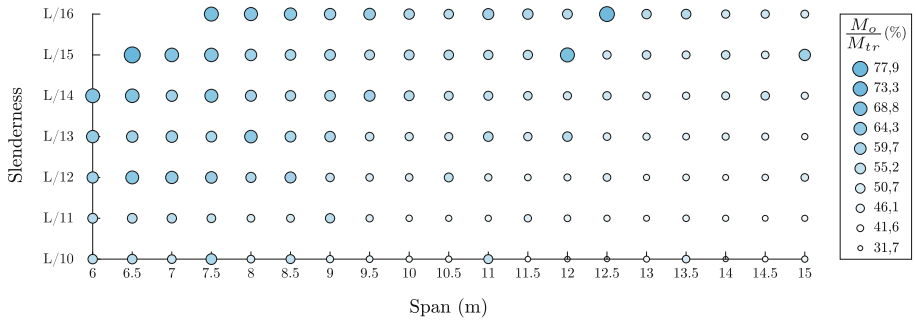


Fig. 7. Evolution of the weight gain with the span and the slenderness (M_o - mass of the optimised beam, M_{tr} - mass of the traditional prismatic beam).

reinforcements are calculated. As presented in Fig. 2, there are three optimisation parameters, the number of rods in a reinforced section, the diameter of those rods and the spacing between two reinforced sections. The peaks are due to particular cases for which the minimum possible effective shear reinforcement was obtained for small spacings between two adjacent reinforced sections. This results in a high consumption of inefficiently used concrete. Figure 8 gives a schematic representation of some beam designs for a span of 12 m. The first beam ($L/15$) highlights this phenomenon. A reformulation of this problem, in the form of a multi-objective optimisation problem taking into account both the effective steel section and the spacing, allows for a better control of the concrete savings.

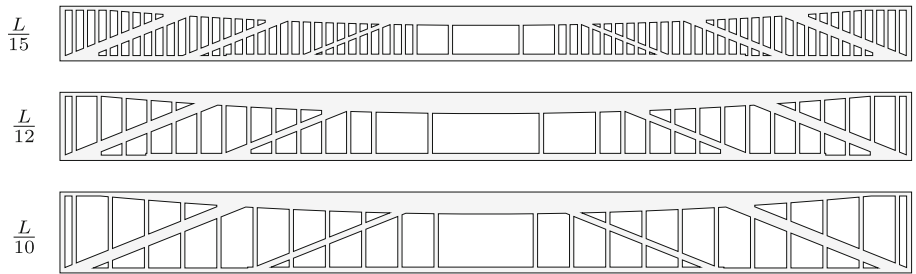


Fig. 8. Examples of beam designs obtained when the only criterion for the optimisation of the ties is the effective steel section.

Concrete Savings. Most importantly, Fig. 7 shows ratios between 31,7 to 77,9% and thus demonstrates a weight gain in the range of 22 to 68%. In reinforced concrete buildings, beams commonly have a slenderness of about $L/10$ to $L/12$ and a span of 6 to 9 m, a range for which our approach leads to considerable savings of about 32 to 58%. Those values of slenderness are not considered to be

optimised from a mechanical point of view but they provide an important lever arm. This enables to have low ratios of steel which tends to ease the fabrication process both in terms of assembly of the rebars and pouring of the concrete. But even for lower slenderness, the savings remain important, ranging from 22 to 45%.

These gains need to be seen in perspective. For traditional office buildings, for which the frame is the predominant structural design, there is a direct saving but also an indirect saving through a global reduction of the self weight of the structure. This notably contributes to a reduction of the foundations sizing. For acoustic reasons, traditional housing buildings are more often designed as wall-slab structures. From a purely mechanical point of view, this seems nonsensical in the current context. We see here a challenge that remains unsolved.

4.2 Discussion on the Fabrication

Several technical issues were raised during the construction of the prototype. Firstly, as mentioned in the previous section, the layers' length distribution is critical and would be even more complex to manage for real applications. Typically, for a 7m-long beam with a slenderness of $L/15$, the ratio between the longest printed piece perimeter and the shortest one would be 7.18. Then, the order of magnitude for the precision of the rebars placement, which were manually assembled on a work site, was ten time higher than that of the formwork (both plywood and concrete parts). It was impossible to insert the rebar cage inside the formwork at first. For future applications, it will be necessary to better control each stage of the process, notably by automating the assembly of the rebars. Similarly, an easily replicable method has yet to be found to prevent the displacement of the printed pieces during the vibration of the formwork without making their retrieval too complicated in the hypothesis of a fully recyclable 3D printed formwork. The use of self-compacting concrete is probably necessary.

From an economical point of view, it is clear that a simpler but more robust printing technology should be used. Typically, a 3-axis robot would be more appropriate. The biggest lever however remains the printed material. Currently, a major part of the formwork cost (both economic and environmental) is in the printed concrete because of its high cement content.

5 Conclusion and Perspectives

Reinforced concrete construction industry is marked by an over and inefficient consumption of concrete. This paper presented a strut optimisation approach, compliant with EC2 requirements at ULS, SLS and for construction detailing. This method results in up to 60% raw material savings. The associated fabrication process is enabled by digital fabrication and 3D printing. A 3m-long prototype was built to prove the constructability of beams designed with the proposed method.

The construction industry faces major challenges, notably the environmental crisis and the population growth, in the coming years. We believe that it is necessary to find applicable solutions in the very short term. But, the development and transfer of such solutions to the industry will be determined by the ability of all players at stake to rally around a common purpose. Environmental experts are needed to assess the soundness of digital fabrication processes and economists to assess their viability, structural and material specialists are required to propose new ways of building and confirm the proper mechanical behaviour of their proposals, contractors must ensure their implementation at large scale, ... Our proposal is part of this ongoing effort.

Acknowledgment. The authors are grateful to Léo Demont, Paul Carneau and Nicolas Ducoulombier for their help during the printing of the formwork. We sincerely thank Christophe Bernard for his technical assistance during the whole fabrication process.

This work was made during Mr. Maitenaz doctorate within the framework of an industrial agreement for training through research (CIFRE number 2018/1055) jointly financed by the company VCF TP IDF SA (Vinci Construction France), and the National Association for Research and Technology (ANRT) of France.

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Thermal and Sound Insulation of Large-Scale 3D Extrusion Printing Wall Panel

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Abstract. A 3D printing technology for construction has been developed for some decades. This technology presents a great potential applying into existing construction and is believed to encourage a sustainable construction. This is because of its perceptible benefits of free-form fabrication without formwork, enhanced product quality, minimized waste produced, and reduced labor workforce. The technology also presents consequential automated advancements and is poised to be a disruptive force in the evolving global construction industry. Presently, it is found that many cementitious materials have been developed to have the fresh characteristics suitably for a large-scale extrusion 3D printer. Previous research reported that a large-scale 3D-printed wall panel with the size larger than 1-m by 1-m exhibited better thermal and sound insulating performance characteristics, when compared to a traditional concrete wall panel. These better performance characteristics were indicated when using a high-strength 3D extrusion printing wall panels with the 28-day compressive strength value greater than 50 MPa. The large-scale 3D extrusion printing wall panels having normal 28-day compressive strengths of 25 MPa and 35 MPa should be assessed. This work aims to present results on investigating its thermal and sound insulating performance of the 3D extrusion printing wall panels with mortar having different compressive strengths. Three mortar types having various 28-day compressive strengths are developed and printed into the wall panel with different surface textures using the large-scale 3D extrusion printer. The printed wall panels are investigated on their benefits for thermal and sound insulating performance. In addition, other hardened performance characteristics of mortars developed herein such as density, porosity, flexural strength, drying shrinkage, and thermal conductivity of the mortar materials are evaluated.

Keywords: 3D extrusion printing · Thermal insulation · Sound insulation · Wall panel

1 Introduction

Additive manufacturing technology by cement extrusion also called as “3D extrusion printing” has been widely investigated for the future opportunity for disrupting existing construction techniques. Many opportunities and challenges of this technology are still present [1–10]. There have been many studies to develop the suitable material

formulation for 3D extrusion printer since its performance characteristics especially for the fresh characteristics are much differed from the casted cement mixture. The material development of its fresh characteristics are reported to be able to follow the Bingham-type fluid system [11, 12]. This system has linear shear stress and shear strain behavior as shown in Eq. (1).

$$\tau = \tau_0 + \eta\dot{\gamma} \quad (1)$$

where τ = resultant shear stress; τ_0 = yield stress; η = plastic viscosity; and $\dot{\gamma}$ = applied shear strain.

According to previous inventions [13, 14], the 3D extrusion printing mortars were formulated with several designed strengths. These different strength classes of the extrusion printing mortar allow the material utilized in various applications; whereas, their fresh performance characteristics are similar. Bentz et al. [15] reported that fresh performance characteristics could be adjusted via water content adjustment and the combination between retarder/accelerator added while the desired mechanical performance characteristics could be adjusted via cement: limestone powder ratio. The mix ingredient of the 3D extrusion printing mortars is one of the key parameters representing the 3D-printed product quality.

Much research has been studied on its fresh and mechanical performance characteristic of the 3D extrusion printed products. Several construction products have been developed using 3D extrusion printer including wall panel, bridge, column, building [16–18]. Little has been done regarding thermal and sound performance characteristics when printing as a building. Prasittisopin et al. [19] indicated that 3D printed wall panels could enhance the thermal insulation characteristics; that is, the maximum temperature of the 3D printed wall reduced by 4.7 °C when compared to the traditional wall panel and this led to the reduction of energy consumption of the building by almost half. The 3D extrusion printing structure significant reduce the energy consumption of the building due to its freeform design allowing the air-gap inside the panel. Robati et al. [20] reported that mix design of concrete highly influenced its thermal performance especially by changing the aggregate density and material proportion. Hence, this study aims to investigate the thermal and sound performance characteristic of 3D printed wall panels with three different desired strength mortars. The thermal performance characteristics investigated includes effects of different materials' strength, and effects of different panels' textures.

2 Materials and Methods

2.1 Materials

The 3D extrusion printing mortar was reported to have unique performance characteristics that could be 1) pumpable, 2) printable, 3) buildable, and 4) suitable open time [21]. Hence, the 3D printing extrusion material used in this study was formulated internally. Its compositions compose of ordinary portland cement, rapid-set cement, silica fume, pulverized fly ash, hybrid fibers, crushed limestone aggregate, and

accelerator/retarder admixtures. More detail assessment of the properties can be found in Chalermwut et al. [13]. Three classes of the 3D extrusion printing mortars were assessed. Their performance characteristics of the 3D printing extrusion mortar are shown in Table 1, respectively. Water used in this study was tap-water at ambient temperature. Insulated foam panels with the thickness of 0.1 m were procured locally and then fabricated as an adiabatic system with the size of 1.0 m by 1.0 m by 0.6 m.

Table 1. Performance characteristics of 3D extrusion printing mortars.

Properties	Unit	High	Medium	Low
Flow	%	≥ 55		
Air content	%	6.5	8.0	8.5
Density	kg/dm ³	2.28	2.24	2.15
Compressive strength at 28 days	MPa	64	41	29
Flexural strength at 28 days	MPa	20	14	8
Bonding strength at 28 days	MPa	2.1	1.9	1.4
Tensile strength at 28 days	MPa	6.7	5.6	5.4
Thermal conductivity	W·K ⁻¹			

2.2 Methods

This method section consists of 1) fabrication method and 2) characterization method.

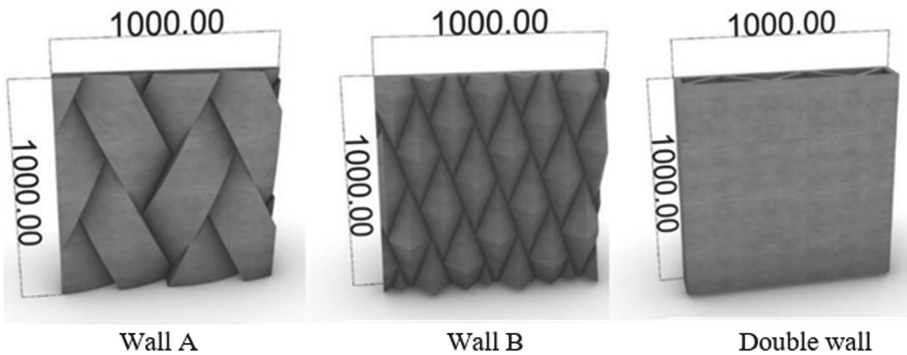


Fig. 1. 3D printed wall panels with different patterns.

Fabrication Method. Three 3D extrusion printing mortars were mixed with water in the mortar mixer with the water to cement ratio of 0.12 for 6 min to have the suitable rheology for extruding. The printing machine is BigDelta 6.0 MT developed by WASP (Massa Lombarda, Italy). After mixed the mortar was then loaded into the feeder of the 3D printing machine and extrude by the extruded nozzle with the diameter of 3 cm. The 3D printed wall panels were extruded using the 3D printing machine with the size

of 1.0 m by 1.0 m by 0.1 m and each layer has the layer height of 1 cm. Three different patterns were designed as shown in Fig. 1. After extruded, the 3D printed wall panels were cured in the ambient condition for 28 days before testing the thermal and sound insulation performance.

Characterization Method. The 3D extrusion printing wall panels having three different desired strengths and three different patterns were determined including the thermal insulation performance and sound insulation performance.

Thermal Insulation Performance. Figure 2 exhibits the field test of thermal insulation characteristics of the 3D extrusion printing panel. Each panel was fabricated and sealed in a foam insulation cabinet facing to the south. The surface temperatures of both inside wall and outside walls were collected in ten-minute interval using a thermocouples (PL-90-11; Tokyo Sokki Kenkyujo; Japan) embedded at the center of each panel with a data logger TDS-540; Tokyo Sokki Kenkyujo; Japan). The measurement range of the equipment is $-10\text{ }^{\circ}\text{C}$ to $200\text{ }^{\circ}\text{C}$, and the accuracy is $\pm 0.5\text{ }^{\circ}\text{C}$ or $\pm 0.5\%$. Data were collected for approximately 3 days. The temperatures within 3 days was averaged into 24-h period. In the meantime, the outside air (ambient) temperature was also measured.

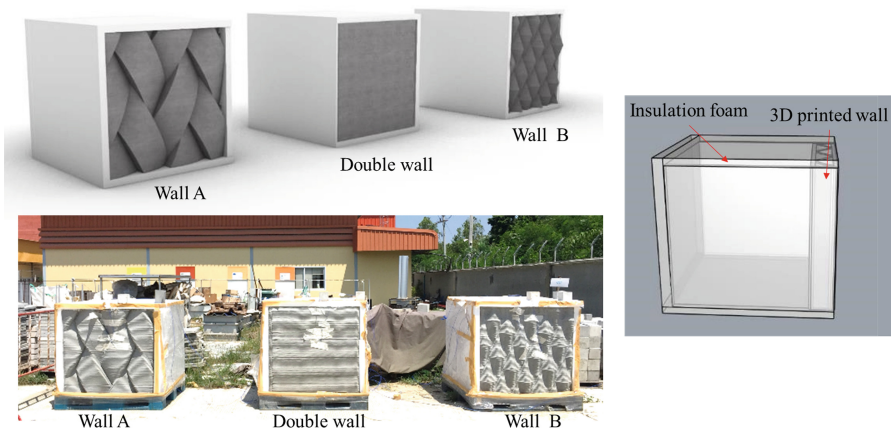


Fig. 2. In situ thermal insulation performance testing program.



Fig. 3. Sound insulation performance testing program following ASTM E336.

Sound Insulation Performance. The sound insulation performance of the 3D extrusion printing wall panels was evaluated following ASTM E336 standard method [22]. The sound insulation testing program is exhibited in Fig. 3. The receiving room has a size of 66 m³. An acoustic source has the sound spectrum at the frequency ranging from 100 to 2500 Hz and 12 locations inside the receiving room were assessed.

3 Results and Discussion

This section explains tested results of 1) in situ thermal insulation performance and 2) sound insulation performance.

3.1 Thermal Insulation Performance Results

Effects of Compressive Strength of 3D Printing Mortar

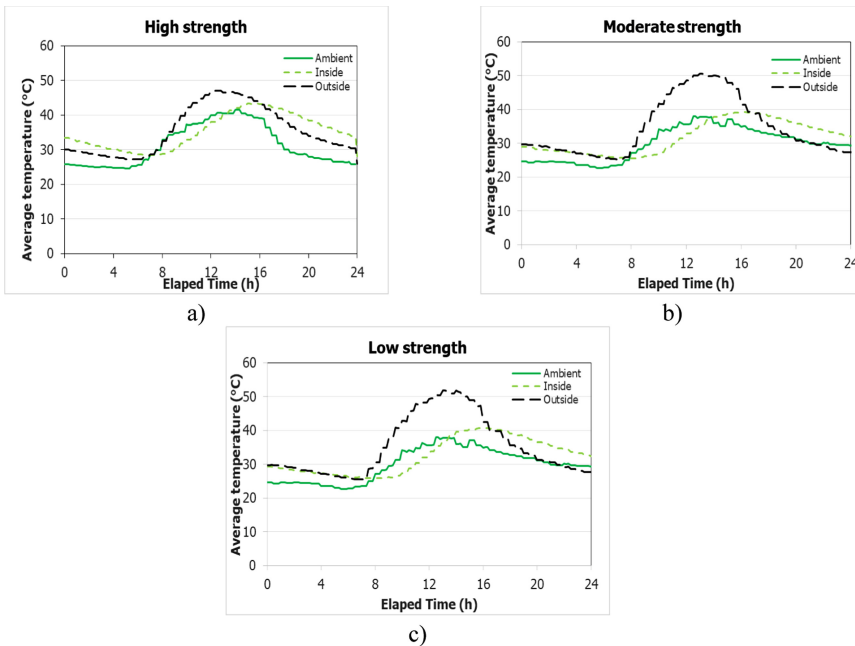


Fig. 4. Plots of average surface temperature over time of the doubled-wall 3D printing panels made from a) high-strength mortar; b) moderate-strength mortar; and c) low-strength mortar.

Tested results shown in Fig. 4a) indicate the average temperatures of doubled-wall 3D printing panels using the high-strength mortar measured at ambient, inside surface of the testing cabinet, and outside surface of the testing cabinet. The elapsed times ranging from 0 to 8 h and from 20 to 24 h represent the nighttime condition and the elapsed

time ranging from 8 to 20 h represents the daytime condition which the outside panel is exposed to the sunlight. At the elapsed time of 0 to 8 h, the average temperature of the inside temperature is higher than the outside and ambient temperature, respectively. This means the inside surface absorbs the heat and dissipates slower than the outside surface temperature, and ambient temperature. At the elapsed time ranging from 8 to 14 h, the temperatures of the outside surface temperature is higher than the ambient, and the inside surface temperature. This means when the panel is exposed to the sunlight, the outside panel absorbs heat quickly due to the heat conductivity of the material (shown in Table 1). The ambient temperature increases afterward, following by the surface temperature of the inside surface panel. The 3D printing panel acts as the thermal insulator. At the elapsed time of around 14 h, all measured temperatures are dropped. The surface temperature of the outside panel drops faster than the ambient. While the surface of the inside panel is stable for some time before dropping; meaningly, the maximum temperature (43.4 °C) of the inside panel delay. From this results, the outside panel dissipates the heat faster than the ambient; whereas, the inside panel effectively preserves the heat. Therefore, at the end of the day, the surface temperature of the inside panel is higher than outside panel and ambient, respectively. Figure 4b) shows the tested results of the average surface temperatures over time of the 3D printing panel made from moderate-strength mortar. Results indicates the similar patterns to as the 3D printing panel made from high-strength mortar. The 3D printing panel acts as the thermal insulator. However, the maximum temperature of the inside wall made from moderate-strength mortar is 42.7 °C, lower than the maximum temperature of the high-strength mortar by 0.7 °C. The average surface temperatures of the 3D printing wall made from low-strength mortar over time measured at the inside wall, outside wall, and ambient condition are shown in Fig. 4c). Results indicate that the temperatures performs the similar manner to the other 3D printing panels and the 3D printing panel made from the low-strength mortar acts as thermal insulator. The maximum temperature of the inside wall recorded is 40.7 °C which is lower than the moderate-strength and the high-strength by 2.0 and 2.7 °C. The lower maximum temperature means the better efficient insulator. The 3D printing panel made from the low-strength mortar performs the most efficient heat insulator. This is believed to be due to the lighter density leading to higher porosity. Asadi *et al.* [23] reported the cement-based materials having lower densities is the promising product to reduce the heat transfer and energy consumption regarding the lower thermal conductivity. The density of the 3D printing mortar directly affects the thermal insulation performance characteristics of the 3D printing panel.

Table 2. Temperature performance and energy consumption of the 3D printing panels made from mortars with different strengths.

Classification	High strength	Moderate strength	Low strength
Maximum temperature of inside wall (°C)	43.4	42.7	40.7
Kinetics of temperature rise of inside wall (°C/h)	2.0	2.0	1.8
Kinetics of temperature rise of ambient (°C/h)	1.8	1.8	1.8
Relative energy consumption (%)	100	98	93

Table 2 exhibited the temperature performance and energy consumption of the 3D printing panel made from different mortars. Results of the maximum temperature of the 3D printing panels having different mortars indicates that when the mortar having higher compressive strength, the maximum temperature of the inside wall is higher. Kinetics of temperature rise of inside representing how quick the heat transfers through the AM panel of the structure. The slower the kinetics indicates the better heat insulated system. Results indicate the kinetics value of the panel made from the low-strength mortar is 10% lower than the moderate-strength and high-strength mortars. Therefore, the heat transfer of the 3D printing panel made from the low-strength mortar is relatively 10% better than the others. When compared with the kinetics of temperature rise of the ambient, the kinetics of the 3D printing panels made from the high-strength and moderate-strength mortars exhibited higher value than the ambient; meaningly, the heat transfer of these 3D printing panels is faster than in the air. Whist, the kinetics of the 3D printing panel made from low-strength mortar is equaled to the ambient. This allows the 3D printing panel made from the low-strength mortar to have the same heat transfer properties as the air. In addition, a relative energy consumption by the calculation of Zhou et al. [24]. The relative energy consumption (C) is calculated in Eq. (2).

$$C(\%) = \frac{\Delta T}{T_{avg} - T_{eco}} \times 100 \quad (2)$$

where ΔT = maximum temperature of inner wall; T_{avg} = daylight average temperature (= 35 °C in Thailand); and T_{eco} = general adopted temperature setting for the air-conditioning system during summer (= 26 °C in Thailand).

Results of the relative energy consumption indicate that the 3D printing panel made from the high-strength mortar consumes more energy by 2% than the moderate-strength mortar and by 7% than the low-strength mortar. This also proves that using the lower-strength mortar having lower density allows the 3D printing panel to perform better thermal insulator.

Effects of Texture of 3D Printing Panel

In this section, the thermal performance characteristics of the 3D printing panels made from the moderate-strength mortar having three different patterns over 24-h period are shown in Fig. 5. Results indicate that the average surface temperature of the outside wall for all textures has the maximum values higher than the inside wall and inside air wall (Table 3).

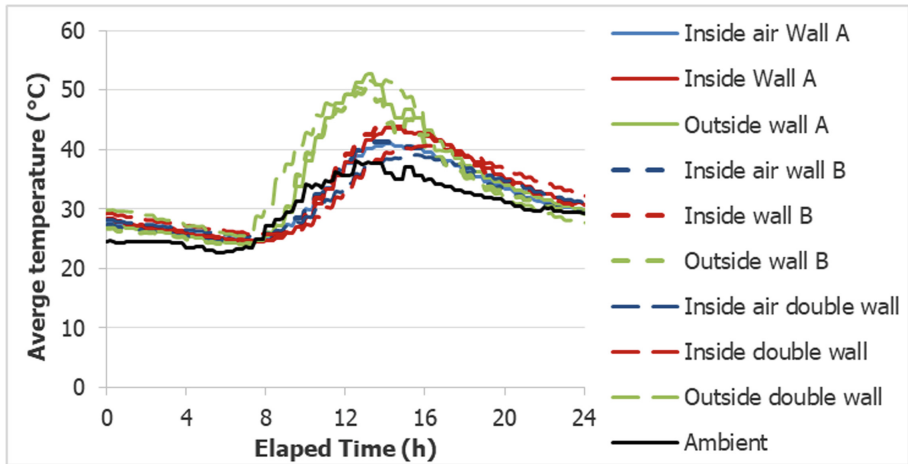


Fig. 5. Plots of average surface temperature over 24-h period of the 3D printing panels made from moderate-strength mortar with three different patterns compared to temperatures in ambient condition.

Table 3. Temperature performance and energy consumption of the 3D printing panels made from moderate-strength mortars with different textures.

Classification	Double-wall	Texture-1	Texture-2
Surface area (m ²)	1.0	1.6	1.2
Volume of air pocket in panel (dm ³)	0.072	0.023	0.023
Maximum temperature of the inner wall	42.7	45.1	46.0
Kinetics of temperature rise of inner wall	2.0	2.3	3.2

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